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Energy Storage Systems Program Report for FY99

John D. Boyes

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Energy Storage Systems Program Report for FY99

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Abstract

Sandia National Laboratories, New Mexico, conducts the Energy Storage Systems Program, which is sponsored by the U.S. Department of Energy's Office of Power Technologies. The goal of this program is to develop cost-effective electric energy storage systems for many high-value stationary applications in collaboration with academia and industry. Sandia National Laboratories is responsible for the engineering analyses, contracted development, and testing of energy storage components and systems. This report details the technical achievements realized during fiscal year 1999.

Acknowledgment

Sandia National Laboratories would like to like acknowledge and thank Dr. Imre Gyuk of the U.S. Department of Energy's Office of Power Technologies for the support and funding of this work. Our appreciation is also extended to all of the contributing organizations that have been instrumental in the success of many ESS Program activities in FY99.

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Acronyms and Abbreviations

ABESS	advanced battery energy storage system
AES	Advanced Energy Systems (a company) or advanced energy storage
AGM	adsorbed glass mat
AOP	Annual Operating Plan
APC	Applied Power Corporation
APS	Arizona Public Service
ASD	adjustable-speed driver
ASU	Arizona State University
AVEC	Alaska Village Electric Cooperative
BES	battery energy storage
BESS	battery energy storage system
BEWAG	Berliner Kraft und Licht
BOP	balance of plant
CAES	compressed air energy storage
CAS	compressed air storage
CCC	complete capacity cycle
CMC	Complete Meeting Concepts
CP	In reference to PV model
CPES	Center for Power Electronics Systems
CRADA	cooperative research and development agreement
CSI	Campbell Scientific Inc.
CSV	comma-separated variable
CT	current transformer
CVCI	constant voltage, constant current
D/A	digital/analogue
DAS	data acquisition system
di/dt	delta current/delta time
dv/dt	delta velocity/delta time
DC	direct current
DLC	double-layer capacitor
DOD	depth of discharge
DOE	U.S. Department of Energy
DPQ	Distribution Power Quality
DUA	Distributed Utility Associates
EECI	Electrochemical Engineering Consultants, Inc.
EESAT	Electrical Energy Storage Systems Applications and Technologies
EOD	end of discharge
EOL	end of life
EMC	electric membership cooperative
EPRI	Electric Power Research Institute
ESA	Energy Storage Association
ESD	electronic selector device
ESS	energy storage system
ETO	emitter turn-off thyristor
EU	Energy United
FACTS	flexible AC transmission systems
FES	flywheel energy storage
FY	fiscal year
GE	General Electric
GNB	GNB Technologies, Inc.
GTO	gate turn-off thyristor-oriented
HEV	hybrid electric vehicle

Acronyms and Abbreviations (continued)

HTS	high-temperature superconductivity
I/O	input/output
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IGBT	insulated gate bipolar transistor
IGCT	integrated gate commutated thyristor
ILZRO	International Lead Zinc Research Organization
IPC	Idaho Power Company
ISO	independent system operators
ISOC	intermediate state of charge
KCPL	Kansas City Power and Light Co.
KPU	Ketchikan Public Utility
kVAR	kilovolt ampre reactive
kW	kilowatt
LANL	Los Alamos National Laboratory
LBX	an operating mode
LED	light emitting diode
Li-ion	Lithium-ion
LL	load leveling
LL+SR	load leveling with spinning reserve
LVD	low-voltage disconnect
LVDR	low voltage disconnect and reconnect
MB	magnetic bearing
MG	motor/generator
MOU	memorandum of understanding
MP&L	Metlakatla Power and Light
MW	megawatt
NASA	National Aeronautics and Space Administration
NCDC	National Climatic Data Center
NEMA	National Equipment Manufacturer's Association
NERC	National Energy Reliability Council
NIST	National Institute of Standards and Technology
NOAA	National Oceanographic and Atmospheric Administration
NRECA	National Rural Electric Cooperative Association
NREL	National Renewable Energy Laboratory
O&M	operating and maintenance
O/C	open circuit
OGPS	off-grid power system
OPT	Office of Power Technologies
ORNL	Oak Ridge National Laboratory
PAR	project authorization request
PC	pilot cell
PCE	power cost equalization
PCL	premature capacity loss
PCS	power conversion system
PEBB	Power Electronic Building Blocks
PG&E	Pacific Gas & Electric Company
PI	proportional integral
PLC	programmable logic controller
PNM	Public Service Company of New Mexico
POA	plane of array
PQ	power quality
PQDIF	power quality data interchange format

Acronyms and Abbreviations (continued)

PREPA	Puerto Rico Electric Power Authority
PS	peak shaving
PSEL	PV System Evaluation Laboratory
PT	potential transformer
PV	photovoltaic
PV4U	Photovoltaics for Utilities
PWM	pulse width modulation
R&D	research and development
RAPS	remote area power supply
RFI	request for information
RFP	request for proposal
RFQ	request for quotation
RGS	renewable generation and storage
rms	root mean square
rpm	revolutions per minute
SAMSOM	Solar and Meteorological Surface Observational Network
SCADA	supervisory control and data acquisition
SCC	Standards Coordinating Committee
SCE	Southern California Edison
SEE	Southeastern Electric Exchange
SEM	scanning electron microscopy
SES	a company (manufacturer)
SMES	superconducting magnetic energy storage
SNL	Sandia National Laboratories
SOA	safe operating area
SOC	state of charge
SOW	statement of work
SPI	Superconducting Partnership Initiative
SPQS	Substation Power Quality System
SPWM	sine-triangle pulse width modulation
SR	spinning reserve
STAR	Solar Test and Research
StatCom	Static Synchronous Compensator
TBD	to be determined
T&D	transmission and distribution
Tc	critical temperature
TGA	thermogravimetric analysis
TPQ	transmission power quality
UE&C	United Engineers & Constructors
UL	Underwriters Laboratory
UMR	University of Missouri-Rolla
UPFC	unified power flow controller
UPS	uninterruptible power supply
USFS	U.S. Flywheel Systems
VAR	volt amp reactive
Voc	volt open circuit
Vr	disconnect voltage
VRLA	valve-regulated lead-acid
Vrr	reconnect voltage
WTG	wind turbine generator
XPS	x-ray photoelectron spectroscopy
XRD	x-ray diffraction
ZBB	ZBB Technologies, Inc.

Energy Storage Systems Program Annual Report for Fiscal Year 1999

1. Executive Summary

Introduction

The U.S. electric utility industry is undergoing revolutionary change as a result of deregulation and competition, seeing limitations on installing new conventional generation and transmission and distribution (T&D) equipment and greatly reduced resources for research and development (R&D). The United States Department of Energy (DOE)/Office of Power Technologies (OPT), through its Energy Storage Systems (ESS) R&D Program at Sandia National Laboratories (SNL), continues to work cooperatively with the electricity supply industry and the manufacturing sector to develop energy storage systems that will play a vital role during and after this transition period. In doing so, the ESS Program is furthering the goals of the DOE by developing technology that can be used by industry to (1) strengthen the nation's energy security in terms of electricity supply, (2) reduce the environmental impact of electricity generation and T&D through the increased use of renewables, and (3) increase the global economic competitiveness of U.S. industry with more reliable, higher quality, and low cost electricity.

The ESS Program is conducting focused R&D, leveraged by U.S. industry, to make possible the widespread use of energy storage systems for electricity system applications and for renewable generation applications. Its goal is the development of new energy storage systems with superior performance and higher energy densities at competitive prices. The program includes research on a portfolio of storage technologies such as batteries, flywheels, and superconducting magnetic energy storage (SMES).

The ESS Program balances the R&D of promising new technologies with focused analytical and educational tasks. The ESS Program is organized into three interrelated elements:

Integration
- System Development
- System Field Evaluation

Components
- Development
- Evaluation

Analysis
- System Studies
- Technology Assessments

Highlights

The FY99 Annual Operating Plan (AOP) for the ESS Program was used as a guide for program implementation. The Mobile PQ2000 highlighted the hardware testing projects by being successfully moved 600 miles and set up for operation at an industrial polymer processing plant in five calendar days. Three significant new projects were initiated. The ESS Program is teaming with the State of Alaska Energy Authority, Chugach Electric Cooperative, other Alaska utility organizations, and the National Rural Electric Cooperative Association (NRECA) to design, build and demonstrate a 20- to 30-kW energy storage system for small Alaskan villages. The development of a high power semiconductor switch and emitter turn-off (ETO) thyristor, which began late in FY98 with Virginia Tech, shows significant promise of increasing the capability of the power conversion system (PCS) for energy storage systems. A transmission power quality (TPQ) study was initiated with the Southeastern Electric Exchange (SEE) to study the power quality of the existing transmission system in the Southeastern United States to provide data necessary for design of future energy storage systems. The program continued its international relationships with the completion of the International Energy Agency (IEA) Annex IX work, participation in the Sixth International Conference on Batteries for Utility Energy Storage, and continued cooperation with the International Lead Zinc Research Organization (ILZRO) on valve-regulated lead-acid (VRLA) battery reliability and remote area power supply (RAPS) initiatives.

The following sections describe the key highlights of the program for FY99.

Integration

System Development

Advanced Battery Energy Storage System (ABESS): The zinc/bromine battery is an emerging technology that has many attributes that make it attractive for energy storage applications. The main advantage of the zinc/bromine battery system is good gravimetric energy density, which results in a modular, transportable battery system with sufficient capacity to be placed anywhere on the utility grid. The battery is made almost entirely from plastic (high-density polyethylene), which makes it cost-competitive with lead-acid batteries at high-volume production without the hazardous manufacturing and recycling concerns. Also, the battery operates efficiently over a wide temperature range, functions under intermittent charge/discharge conditions, and can experience complete discharge hundreds of times without damage.

The objectives of the ABESS project are to design, fabricate, evaluate, and optimize a zinc/bromine battery system suitable for electric utilities. The soundness of the battery technology was demonstrated, and new larger cell stacks, designed for an electric utility battery, were developed during previous contracts between ZBB and SNL. The end product of the present contract is to demonstrate a 400-kWh system at a utility installation. Based on the results of this testing and utility interest, larger systems may be tested in the future.

In FY99, a 50-kWh module was successfully tested to demonstrate the operation of a single module connected to the controller with and without utility power. This strategy will simplify the design of the control for the battery system by enabling it to function as an uninterruptible power supply or as a RAPS.

Alternate Renewable Generation and Storage (RGS) System Designs to Improve Battery Performance: An investigation of alternative configurations to optimally use lead-acid batteries in renewable hybrid systems began in the third quarter of FY98. The purpose of this project is to devise alternative configurations for renewable hybrid systems that will allow more optimal charging of the lead-acid batteries in these systems.

The effort during FY99 involved building increasingly sophisticated versions of the breadboard hardware and then testing this hardware with more fully developed versions of the software required for its operation. When the breadboard was first developed, testing could be performed with cycles at a shallow depth of discharge (DOD). As the development progressed, however, it was necessary to test it with cycles of 50% DOD, so that the development would more closely mimic lead-acid batteries in the field.

In the latter part of the second quarter and the remainder of FY99, the alternative configuration system was operating more or less continuously. Operation during this time consisted of automated cycling with discharges and charges each lasting approximately seven hours in duration. In the last few weeks of FY99, the cycling was continuous, under automated control, with almost no interruptions for weeklong periods.

Small Village System Integration: Chugach Electric Cooperative, the State of Alaska Energy Authority, other Alaska utility organizations, and the NRECA in collaboration with the ESS Program are designing, building, and demonstrating a 20- to 30-kW energy storage system for small Alaskan villages. The purpose of this integration, test, and field evaluation project is to quantify the benefits of battery storage for small villages that have diesel-only generation. This study is collaborating with a similar study by ESS and the U.S. Agency for International Development. A system feasibility study was initiated in FY99. If appropriate, a prototype system will be assembled and undergo initial testing and debugging at a test bed in Anchorage under controlled conditions.

The feasibility study was initiated in June 1999. A contract was placed with Sentech, Inc., to conduct the study and prepare a report describing the results. The SNL and Sentech study team visited Alaska and had discussions with the director and staff of the Alaska Energy Authority, with Chugach Electric Cooperative staff and management, and with Alaska Village Electric

Cooperative (AVEC) personnel. The perspectives of each organization were obtained, and there was support for the project. The objectives of the Alaskan organizations for this project are to find ways to use advanced technology to save diesel fuel and associated costs, reduce pollution and environmental threats from fuel transportation and storage, and improve the economic conditions of the more than 200 remote communities in Alaska.

Renewable Generation and Storage and Related Projects: In FY98, the ESS Program issued a request for proposal (RFP) for the first phase in this project. Contracts were awarded to three companies to conduct three-month studies that focused on integrating energy storage systems with renewable energy generation. These studies were completed in FY98 and the results are summarized in SNL's ESS Program Report for FY98, SAND98-0883.

In FY99, the final reports for each of the three contracts were published:

AeroVironment, Inc.—SAND99-0936, *Solar-powered Systems for Environmental Remediation*

Solarex—SAND99-1477, *Investigation of Synergy Between Electrochemical Capacitors, Flywheels, and Batteries in Hybrid Energy Storage for PV Systems*

Ascension Technology, Inc.—SAND99-0935, *System and Battery Charge Control for PV-powered AC Lighting Systems*

The ESS Program determined that the results for Phase I were satisfactory enough to justify moving to Phase II of the project. Consequently, a second RFP was issued soliciting bids for follow-on work. Three proposals were received and evaluated by ESS Program staff and staff from the Photovoltaics Program at SNL. One contract for Phase II work was awarded to Ascension Technology, Inc., now a division of Applied Power Corporation (APC). Ascension Technology's final report for the Phase II work was submitted at the end of FY99 and will be published in FY2000. The results of Ascension's Phase II work, as documented in the final report, are summarized in Chapter 2 of this report.

System Evaluation

Mobile PQ2000: On May 13, 1999, the Mobile PQ2000 (2 MW for 15 seconds, trailer-mounted system) was removed from the Virginia Power Iron Bridge facility in Richmond, Virginia, and began its journey to the S&C Electric Company plant in Chicago, Illinois, where it will undergo field testing. The unit, which was installed by S&C to protect its polymer product fabrication plant, arrived on Friday, May 14, 1999, and was on line and fully operational by Tuesday, May 18.

VRLA Battery Test at Vernon: In the beginning of FY96, a contract was awarded to GNB to perform testing over a four-year period of a final deliverable from a development contract. Costs for the test are being shared by GNB at 50%. The 250-kW/500-kWh deliverable battery has been incorporated into a 3.5-MW/3.5-MWh battery system that was installed by GNB at its lead-recycling center in Vernon, California. To match the rest of the battery system planned for Vernon, and because of its established production capability, the battery design chosen as the deliverable was the ABSOLYTE IIP. The primary application for the battery system at Vernon is to provide emergency backup power to critical loads at the facility dealing with environmental (air emission) controls. It is also being used in a peak-shaving mode for demand reduction that will lower electricity demand charges for the facility and take advantage of lower off-peak energy costs.

The battery system has been in operation since the first quarter of FY96. Tests of the peak-shaving mode began in July 1997 and continued in FY98 and FY99. A primary objective of these tests is to find the optimum trigger power level for the battery system to supply the plant demand during peak shaving while the battery energy storage system (BESS) continues to perform its primary function of supplying backup power for emissions equipment at the lead smelter.

At the beginning of FY99, practical engineering problems with ground-fault detection circuits that were an issue at Vernon in the past were resolved so that ground-fault alarms were no longer continuous. The peak shaving trigger level was progressively decreased during the winter months until it reached 1275 kW in April. The optimum winter peak shaving setting is estimated to be near 2925 kW. In May, the trigger was raised to 3100 kW to accommodate the utility's longer summer season on-peak demand. Choice of BESS peak shaving settings was handed over to the local engineering staff at Vernon in June 1999. Therefore the 3100-kW setting was maintained for several months to allow the local engineering staff to gain more understanding of the facility's on-peak demand characteristics. Peak shaving will begin in the first quarter of FY2000 at this same aggressive level, with anticipation of going lower as the winter season approaches. Finally, in August the Vernon BESS interface computer was replaced to ensure Y2K compliance. A new Windows NT-based system was installed with upgraded software and hardware components. The new interface computer passed all Y2K date tests successfully.

In September 1999, the peak shaving trigger setting was lowered to 3025 kW. During summer on-peak hours, this setting was expected to be near optimal level of peak shaving at which maximum cost savings can be attained while still maintaining the BESS within the proper sate-of-charge (SOC) window to continue peak shaving on any given weekday of the month.

Field Test Data Management for Grid-Connected Systems and for RGS Off-Grid Systems: In FY99, SNL initiated a project to develop a database for fielded battery energy storage systems for off-grid, stand-alone and grid-tied systems that are currently in operation. The purpose of the database is to provide information on the operation and management of these existing systems in order to learn how to design future systems and avoid problems identified from this evaluation. The database is intended to provide practical field performance data for potential customers.

Four contractors were selected for the initial phase of the project, two for off-grid analysis and two for on-grid analysis. Their first task was to identify a site that would provide historical data for an energy storage system in operation that met the criteria for analytical tasks called out in the contract. Secondary tasks were also defined to determine the adequacy of the data acquisition system (DAS) used for the fielded systems, determine the adequacy of the battery management strategy applied to the fielded system, and to make recommendations for ways to increase the reliability of the DAS for fielded systems. Four sites were selected and the data obtained and analysis begun by year's end.

PREPA Systems Lessons Learned: A 20-MW, 14-MWh BESS was installed in June 1994 at the Sabana Llana substation near San Juan, Puerto Rico, primarily to mitigate under-frequency load shedding. The owner-operator, Puerto Rico Electric Power Authority (PREPA), and the architect/engineer and supplier firms learned many valuable lessons, from planning through the first four years of operations, about the largest "commercial" battery system in operation in an electric utility application. PREPA collaborated with the ESS Program to compile a "lessons learned" report for the facility. The report, *Lessons Learned from the Puerto Rico Battery Energy Storage System* (SAND99-2232), published in September 1999, is available in both English and Spanish.

Peru Small Field Test Monitoring: In July 1997, the ILZRO, the Energy Storage Association (ESA), the Solar Energy Industries Association, and the country of Peru signed a memorandum of understanding (MOU) for a collaborative project. The objective of the first phase of the project was to perform a feasibility study for photovoltaics in combination with storage, power electronics, a genset, and controls for use in remote villages in the Amazon River valley.

The feasibility study included a discussion of system and component sizing, performance and economic benefits. The cost of the study was shared by the MOU signatories and the ESS Program. Results of the approximately six-month study are documented in an ILZRO report. The MOU signatories have now started the hardware demonstration phase and are pursuing funding opportunities.

Photovoltaic/Battery Hybrid Controller Field Test: The evaluation of the first photovoltaic (PV)/ battery hybrid controller at the SNL PV System Evaluation Laboratory was completed in FY95. A project plan was developed that called for the installation of the second prototype control unit at a site that could provide at least a 15-kW PV array, a 200-kWh battery, 30-kW genset, and a variable load that would simulate the electric power consumption of a small village. A multiyear operational test plan was successfully negotiated with Arizona Public Service (APS) to perform a complete system field test of the controller at the APS Solar Test and Research (STAR) Center in Tempe, Arizona. The overall objective of the DOE/ SNL project at STAR is to develop an operational strategy for solar hybrid systems, which include energy storage, that will maximize performance and minimize life cycle cost of these systems. An MOU and a loan agreement were finalized in FY97. The MOU provided for the loan of a state-of-the-art inverter/controller and a DAS for up to three years. APS obtained a tubular gel valve-regulated lead-acid battery under a special cost sharing agreement with Yuasa, Inc., to expand the test results to determine whether the gel technology battery was best suited for the hybrid operational environment. A special hybrid test facility was constructed at STAR to house the battery, inverter/controller, and natural gas genset. The STAR Center, with nominal loads of 2 to 35 kW, provides the load for the test program. Two multiyear contracts were placed in FY98 to provide operation and maintenance for the DAS and in-depth analytical support for data generated by the system. By the end of FY99, after more than two years of service at the STAR Center, the consensus is the Yuasa DGX85-11 VRLA-Gell batteries have performed well.

Data Analysis from PV/Hybrid Controller Testing: Following a competitive bidding process, which began late in the first quarter of FY99, a contract for analytical support was awarded in early February to Electrochemical Engineering Consultants, Inc. (EECI), of Morgan Hill, California. EECI was given the task of providing analyses of data collected at the APS STAR Center for the Hybrid Controller Field Test Project.

The objectives for the data analysis that is under way at EECI include:

1. Assist SNL and APS personnel in fine-tuning the Trace controller so that the electricity loads are supplied reliably and efficiently.

2. Ensure that the Yuasa cells in the energy storage battery at STAR are being maintained, repaired, and operated in a way that will maximize life and performance.

3. Make a preliminary determination of the usefulness of gel VRLAs in the solar hybrid application.

The work performed by EECI, beginning on February 4, 1999, has met all three of the objectives for this project. For the first two objectives, this progress is indicated by the results from the testing of the solar hybrid system at STAR.

Integration and Testing of Energy Storage with Flexible AC Transmission System Devices: Flexible AC transmission system (FACTS) devices offer increased flexibility in decentralized control of transmission systems. As the vertically integrated utility structure is phased out, centralized control of the bulk power system will no longer be possible. Transmission providers will be forced to seek a means to get local control to address a number of potential problems such as:

Uneven power flow through the system (loop flows),

Transient and dynamic stability,

Subsynchronous oscillations, and

Dynamic overvoltages and undervoltages.

Adding energy storage to FACTS devices will give them active (real) power capability. Several significant advances were made in the last quarter of FY99. The most important progress has been the incorporation of the BESS into the static synchronous compensator (StatCom) setup. The StatCom is a well-known shunt-connected, commercially available FACTS device. The University of Missouri–Rolla (UMR) project team has designed and built a StatCom and has also designed the topologies necessary to integrate a BESS into a StatCom. The incorporation was delayed because of problems with premature failure of several of the battery modules. This was corrected and the BESS is now fully functional. The StatCom/BESS system has been successfully operated in synchronism with an external AC source.

RAPS Testing Methods Development: The ESS Program continues to coordinate with ILZRO on several collaborative projects. Each project is being cofunded by ESS and by ILZRO at varying levels of cost sharing ranging from 50-50 to 80-20, with ILZRO taking the lead in some projects and ESS in others. A project to define international standard test-cycle regimes for RAPS has scheduled goals for drafting test procedures and reviewing the procedures.

During FY99, the RAPS testing methods development project evolved significantly and began to cement relationships with standards organizations. The goal is to prepare documents that will lead to RAPS design and certification guidelines. With major involvement of the project's co-sponsor, ILZRO, and Energetics, contractor to both SNL and ILZRO on this project, substantial planning was done, documents were prepared, and standards organization interfaces were established. A major decision was made to integrate this project with the existing infrastructure of the Institute of Electrical and Electronics Engineers (IEEE) Standards Coordinating Committee (SCC) 21, Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage. This committee has several standards documents already in preparation or approved that will contribute to RAPS design, testing, and certification guidelines. The documents in process all relate to PV energy systems with battery storage used in a stand-alone mode (no utility connection). SNL, ILZRO, and Energetics will contribute to the PV/battery documents, and will prepare new guidelines for RAPS systems—those that use a renewable generation resource, energy storage, and a fossil-fueled generator in a stand-alone mode.

Components

Development

Advanced Energy Storage Development: In FY97, the ESS Program started to analyze advanced storage technologies (SMES, flywheel, double-layer capacitors [DLCs], etc.) and determine the current state of the art of each technology for both capability and cost. The overall approach to R&D for all advanced technologies will be to (1) identify the industry drivers for each technology, and (2) estimate the compatibility and value of these storage technologies for each of the 13 storage applications (identified in the Phase I Opportunities Analysis performed in FY94) as well as for the combined applications.

The goal of the advanced energy storage (AES) component development project is to support the improvement of AES components. Commercial battery technologies are not included in the scope of this project, but advanced batteries in development are.

In FY99, the ESS Program issued an RFP and funded three companies (Saft, U.S. Flywheel Systems [USFS], and Boeing) to conduct the first phase of a possible multi-phase research project to develop and test components that are large enough to be used in field demonstrations. In Phase I, contractors identified target applications and characterized the applications in terms of benefits and requirements. The contractors then developed storage component specifications and conceptual designs for the most beneficial applications based on state-of-the-art technology. Both prototype and production-scale costs for the technology were then estimated. Finally, contractors created a component development plan and schedule to develop the technology to the prototype field testing stage.

Work on Phase I was completed at the end of FY99. Saft presented results on an advanced battery technology and USFS and Boeing each presented results on flywheel technology. The final reports documenting this work will be published at a later date. A brief summary of each contractor's Phase I work is presented in Chapter 3 of this report.

Battery Simulator Development and Validation: The ESS Program initiated a collaborative project with NRECA in FY97 to develop, validate, and demonstrate simulators of power-quality and peak-shaving systems. The project is providing technical and economic data about peak-shaving and power-quality systems at electric membership cooperatives. More important, the project will introduce a technology assessment that is more exact and no more expensive than a traditional "paper feasibility study."

The ESS portion of the project supports the development and validation of energy storage simulators that will mimic the operation of two BESSs: one that Brockway Standard Corporation operates for power quality (PQ2000) and one that Energy United (EU) Cooperative operates for peak shaving. The NRECA portion of the project supports field demonstrations of the energy storage simulators and the development, validation, and field demonstration of a diesel-generator simulator.

Development and validation of the battery peak shaving simulator at EU's 500-kWh energy storage system at its Statesville, North Carolina, facility was completed. A draft report has been prepared and is under review. During the validation period of August 1998 to April 1999, the utility dispatched the battery system 25 times. Initially, the simulator correctly dispatched the virtual battery 13 times. The software was then modified to improve the dispatch of the virtual battery.

VRLA Reliability Improvement Project: Because SNL believes that VRLA battery technology offers real advantages in utility and renewable energy applications, a VRLA reliability improvement project was formulated. The primary objective of the project is to determine VRLA cycle and calendar life under typical utility battery operating conditions and use modes. The ESS Program and ILZRO have established a collaboration that addresses VRLA reliability issues.

A three-phase project was designed to identify and resolve these battery life issues. Phase 1 involves a survey of the industry, in cooperation with VRLA manufacturers and users, to determine objectively and accurately the status of the technology. Phase I activities were the primary focus in FY99.

Efforts continued in FY99 to encourage return of the surveys, especially by the user group. Manufacturers were also reminded to submit data when they were encountered at professional meetings and during vendor visits. Five manufacturers of VRLA batteries completed surveys that discussed the materials, manufacturing processes, and service-life expectancies of 13 different technologies that serve in stationary applications. The technologies included both gel and adsorbed glass mat (AGM) designs, and the applications included both float and cycling service.

The manufacturers also identified customers who have field experience with their largest volume product, their best performing product, and their least favorable product. The data from the manufacturers' surveys are recorded in an Access database.

By the end of FY99, more than 50 end users had been contacted about the survey, and 10 had agreed to complete it. This should generate a large enough data set to carry out the trend analysis. This analysis will commence as soon as the surveys are received.

ETO Switch Development for PCS: The development of a high-power semiconductor switch, an ETO thyristor, began in the third quarter of FY98. This project entailed the development and testing of a prototype ETO.

ETOs could greatly enhance the PCS, a vital part of the energy storage system used to interface between the storage component and the generation and T&D equipment. At the heart of the PCS are the topological connections of high-power semiconductor switches. To meet the demand of these devices, efforts were made to improve the gate turn-off (GTO) device in the past few years for applications rated in the megawatts. The ETO is a type of GTO device developed at Virginia Tech that could substantially advance high-power ESS applications. Based on the mature technology of current semiconductor devices, the ETO could provide a low-cost, superior solution for megawatt applications.

In FY99, this project was extended to the next phase of ETO development. The objective of the next phase is to build and demonstrate an ETO in a high-power converter with thermal, electric, control, and reliability all being demonstrated and tested in one unit. The preliminary version started at 100 kVA and is anticipated to gradually move up to high power (1 MVA and higher).

Development of Intelligent Controls and Control Strategies for RGS: Both the ESS and PV Programs are interested in the development, design, and testing of an improved, more versatile, and better integrated PCS. Power electronics and the supporting circuitry and software are critical to the eventual wide-scale use of renewables and energy storage technologies for many diverse applications. As documented in the recent SNL report, *Renewable Generation and Storage Project—Industry and Laboratory Recommendations* (SAND98-0591), the DOE ESS Program is embarking on an initiative to address system integration and components in RGS systems. This project includes a competitive procurement with an industry partner to develop an intelligent system controller and evaluate advanced control strategies for power conversion systems used in RGS applications and will include tasks for design, applications analysis, fabrication, and component and system testing.

In FY99, the ESS Program gathered information from the energy storage and PV industries and nonindustry organizations such as the Florida Solar Energy Center and the New Mexico State University Technology Development Institute to clearly define needs, directions, and scope of an improved RGS controller project before initiating a request for information (RFI). The objective was to prepare a clear taxonomy of RGS controls, explore how these controls should be organized, explore which functions are more natural to implement within subsystems and which functions are better suited to more advanced control principles.

Evaluation

VRLA Battery Evaluation: Controlled laboratory tests are the best method to determine battery capacity degradation rates and mechanisms. While batteries in field tests have the same problems, the often uncontrolled variability of the test environment slows the collection of data and makes it difficult to distinguish cause and effect.

Life cycle testing continued in FY99 at SNL on VRLA batteries, which were under test for utility applications, specifically the Yuasa Tubular Gel batteries, the intermediate state of charge (ISOC) test units, and GNB's ABSOLYTE II and ABSOLYTE IIP AGM batteries. The GNB batteries were deliverables from a development contract with GNB. Results from this testing are presented in Chapter 3 of this report.

ABSOLYTE IIP and ABSOLYTE II Testing: Life cycle testing of the ABSOLYTE IIP resumed with Cycle 611 in November 1999, after tester repairs were completed. Capacity continued to decline, falling below 80%, and testing was halted at Cycle 699. After consultation with GNB, a decision was made to try to recover some capacity. A boost charge was performed with little effect. A reference electrode inserted into one cell provided data that indicated possible positive electrode capacity limitations and negative electrode polarization. Tests of an aggressive charge profile are planned for FY 2000.

Life cycle test of the ABSOLYTE II battery also continued in FY99. Air conditioner and tester repairs limited testing time. The capacity declined steadily throughout the testing. Cell 4 end-of-discharge (EOD) voltage became significantly lower than other cells, so it was bypassed. A boost charge was performed with only slight improvement in capacity. Testing was halted at Cycle 506 after several cycles with capacity below rated end of life (EOL). A total of 163 cycles were performed during FY99.

Yuasa Laboratory Testing for Hybrid Environment: In early January 1998, two modules of Yuasa Exide, Dynacel DGX Tubular Gel VRLA cells were received at SNL. A test plan was developed to test these special cycling batteries in a laboratory. The test program emulated the off-grid hybrid operational environment and was run in parallel with the actual field testing of the DGX batteries at the APS STAR Center Hybrid Test Facility in Tempe, Arizona. This test program provided data to compare to the Dynacel battery at STAR, which is being tested in an actual hybrid operating environment. The battery is exposed to a cycling regime that will possibly lead to the optimization of the operating strategy for off-grid RGS applications. Testing began in the summer of 1998 and continued through FY99. All testing has been done in-house at SNL.

Intermediate State-of-Charge Testing: The ISOC test project was initiated in early FY98, and testing of batteries from several participating manufacturers began in the first quarter of FY99 at the SNL test laboratories. Two VRLA gel electrolyte batteries and one AGM battery from three manufacturers were tested as single units and in 60-V strings to determine whether the batteries can operate in an ISOC environment without damage. The ISOC environment allows for better energy management in off-grid applications by not requiring a full 100% recharge following discharge operations. During FY99, the test project required internal technical support to ensure continued and reliable operation of the test equipment and data management system. No external contracts were needed to support this project.

System Evaluation of a 200-kWh Zinc/Bromine Battery at "The Barns": In FY97, after completing a competitive procurement process, the ESS Program initiated a contract with Powercell Corporation to perform in-house tests on Powercell's Zinc-Flow™ battery. The original objective of this project was to characterize the performance of a 9-kWh Zinc-Flow battery.

The project was expanded in FY99 to include the field characterization of 100-kWh units that Powercell calls the PowerBlock. Two 100-kWh PowerBlocks were built and will be field tested at "The Barns," a community theatre at Franklin Park in Loudon County, Virginia. This project will entail monitoring both battery performance and energy use/generation of all the major system components.

The electrical design for the system was completed in the third quarter of FY99. The design allows for optimum use of the BESS. A plan was developed based on this design to measure energy use/generation of the major components. The plan enables the project team to perform energy balances for the entire system. A draft plan for implementation was completed in the third quarter.

Analysis

System Studies

Opportunities Analysis–Phase II: The Opportunities Analysis was conceptualized in FY94 as a two-phase project. Phase II of the project, started in FY98, is an extension of Phase I performed in FY94 and FY95 by the ESS Program. In an earlier, preliminary assessment of national benefits, SNL estimated that the generation and transmission applications of storage could represent $17.2B in national benefits. In Phase I of the Opportunities Analysis, the T&D benefits were found to be significantly higher than previous estimates.

Phase II of the study included a refinement of the technical and economic understanding of the role of energy storage in the utility industry. Increased understanding will help promote appropriate development and more rapid commercialization of utility energy storage systems. The current information is insufficient to estimate market size with a high degree of confidence, especially from a system supplier's perspective. Activity in Phase II primarily focused on the need to characterize the near- and long-term utility application requirements for energy storage.

The first meeting of Phase II of the Opportunities Analysis study was held November 1 and 2, 1998, in Santa Fe, New Mexico. The meeting, which was attended by 15 representatives from the storage and related industries and several Sandians and staff from Energetics, focused on specifying application requirements for stationary energy storage, categorizing them according to a structure meaningful to electricity suppliers and consumers, and reaching consensus on clear terminology. On April 22 and 23, 1999, representatives from DOE/SNL and Energetics and stakeholders from various parts of the energy storage, power electronics, and electric power industries met to conduct Meeting II.

From these meetings emerged definitions for ten individual applications of energy storage that are in general demand and have high value with the electric power producers and their customers. A summary of the requirements of each of the applications and definitions is presented in Chapter 4 of this report.

Value of Storage for a Restructured Utility Industry: The electric utility industry in the U.S. is being restructured and is evolving from a regulated monopoly to a partially competitive, partially regulated group of electricity providers. The public's expectation of plentiful, high-quality, and low-cost electricity for all consumers has not changed, and if anything, will grow in the coming years. Generation, transmission, distribution, and use of electricity will be performed in a great variety of new and evolving ways through the implementation of creative regulatory frameworks, financial instruments, and technologies. One technology that could have tremendous impact is energy storage. A study initiated last year with Distributed Utility Associates (DUA) described several scenarios likely for the utility industry in the future.

DUA completed the study, and the draft final report was received in June 1999. The study describes a series of scenarios in a deregulated utility industry, and it discusses the possible benefits from storage in each case. It discusses ways to expand the envelope of possible storage applications and suggests creative use for storage. It also presents many possibilities for communicating the value and flexibility of storage. This report will be published in FY2000.

Utility Operating Cost Analysis: This task was initiated during FY94 through the placement of a contract with UMR to use the Electric Power Research Institute's (EPRI's) DYNASTORE computer program to perform calculations of utility operating costs with and without BESS. Operating cost savings are one important component of the battery system cost/benefit picture, along with the system capital cost and other projected utility benefits.

Work in this area was continued under a new contract placed with UMR during the second quarter of FY99. A major part of this study is adding the capability to include wind-powered generators in DYNASTORE calculations. The effect of renewable generation on operating costs was then investigated for the Kansas City Power and Light Co. (KCPL) system.

Analysis of the situation with renewables is more complicated and is still not complete, but an indication is emerging that the operating cost benefit of storage in this case may be much larger than that previously estimated for conventional generation sources. The reason for this is that renewable energy sources are not continuously available (e.g., PV at night) and therefore cannot be allocated to certain applications, such as spinning reserve, that require 100% availability. However, the use of energy storage will broaden the range of applications to which renewables can be applied by providing the capability to ride through periods of low renewable generator output. Therefore, storage not only directly replaces more expensive sources of generation, such as combustion turbines, but it also enables renewable generation to serve many of these applications. Since renewables generally have very low operating costs, this significantly increases operating cost savings. Savings can be quite large, four to six times greater than those from adding battery energy storage (BES) alone to a utility system.

This initial study assumed that renewable wind generation is fully allocated to the application and that the wind generation is always on at an average calculated level. Much more work is needed to determine the full effect of variability in the renewable generator output. Potential strategies for allocating the renewable resource also need to be considered in the study.

International Energy Agency Annex IX: The ESS Program at SNL was designated to be the USA Participating Agent in the activities of Annex IX. This responsibility requires attending executive committee and experts meetings in the United States and abroad, coordinating United States representation by experts for the various storage technologies, identifying projects of common interest to the participants, and supporting the implementation of the projects.

Phase 2 of the Annex IX *Electrical Energy Storage Technologies for Utility Network Optimization* work was concluded at the end of FY99. A final report, which was an overview of this work, was submitted in November 1999. Topical reports on Subtasks 1, 2, and 3 were submitted in the third and fourth quarters of FY99.

Subtask 1: Applications Case Studies
Subtask 2: Project Definitions
Subtask 3: Applications Modeling

The *Electrical Energy Storage: Network Applications Case Studies* report focuses on storage systems as solutions for specific problems. It is aimed at users who may be relatively unfamiliar with the field. Preexisting electrical energy storage installations are described from the perspective of the end user application, as distinct from the particular storage technology employed.

The *Project Definitions* report focuses on two energy storage applications: (1) power quality and (2) primary substation applications. The report presents a cost breakdown for the various electrical energy storage system solutions currently available. Generic information is provided without focusing on any single supplier's solution or any particular site.

The *Applications Modeling* report was received in October 1999, and represents the final output of Subtask 3 of Phase 2 of Annex IX. Two electrical energy storage models were introduced. One model was a fully functional, stand-alone power quality applications model. The other was a software specification model for network integration for the applications associated with substation level connected energy storage systems. This model will allow the user to match and size an energy storage system to meet exact technical and economic requirements without the risk of system redundancy or under capacity.

Transmission Power Quality Study: The TPQ study will monitor and define power quality levels of the electric transmission system for a defined 13-state region in the Southeastern United States. A previous study conducted by EPRI characterized power quality levels of the distribution system; however, very little data now exist for customers of transmission networks.

A study team composed of representatives from utilities, SNL, EPRI, and the SEE conducted a scoping study that outlined the project justification, methodology, cost information, and schedule. Monitoring sites will be chosen throughout the Southeast to provide a statistically valid sample of the transmission system. Criteria for choosing sites are voltage class and lightning strike density. Participating utilities will procure, install, download, and maintain appropriate monitoring equipment. The ESS Program will provide funding for the project, in conjunction with cost sharing from industry. Coordination will also take place between the ESS program and other SNL programs that may benefit from this study.

Technology Assessments

Performance and Economic Analysis of SMES, Flywheels, and Compressed Air Energy Storage: The scope of the ESS Program includes a portfolio of energy storage technologies for electric utility applications. The program approach has been to apply expertise gained from work with BES to the development of other storage media, PCSs, peripheral devices, and advanced storage systems that depend on similar components. The ESS Program initiated this analysis project with Energetics, Inc., in FY97 to identify the areas in which program expertise directly applies to this expanded range of technologies and where such program expertise must be developed.

The final report, *A Summary of the State of the Art of Superconducting Magnetic Energy Storage Systems, Flywheel Energy Storage Systems and Compressed Air Energy Storage Systems*, was published in July 1999 (SAND99-1854).

Long- Versus Short-Term Storage Study: A study to characterize the stationary applications and technologies of short- and long-term energy storage was completed by Longitude 122 West, Inc. Applications of energy storage have a wide range of performance requirements. One important requirement is storage time or discharge duration. In this study, applications and technologies were evaluated to determine how storage time requirements match technology characteristics. Comparisons were also made on the basis of capital cost for various energy storage systems operating over a range of discharge times, categorized as short term (< 2 hrs) and long term (2 to 8 hrs). Special categories of very short term (< 1 min) and very long term (a day to weeks) were also considered. The technologies evaluated included batteries (lead-acid and advanced), flywheels (low and high speed), supercapacitors, superconducting magnetic energy storage, compressed air energy storage (CAES), pumped hydro, and hydrogen.

A draft copy of the report was received and is under review. A brief summary of the draft report is included in Chapter 4 of this report.

PCS Magnetics and Functionality Analysis: A previous study conducted by the ESS Program focussed on identifying the state of the art in PCS technology and identified several promising research directions whereby cost and footprint reductions could be achieved. Additionally, the study cited several areas that could potentially contribute to cost reduction, but available information did not permit a thorough assessment. Listed below are two promising ideas that could not be adequately evaluated.

1. Simplify PCS specifications by defining the minimum functionality required for a PCS used as part of an ESS.

2. Improve the magnetics used in the PCS.

The purpose of the work being undertaken at this time is to further evaluate the above areas. As such, this report is an extension of and relies heavily on the previous study. The objective of Task 1 is to determine if there is a standardized approach to specifying PCS functionality that can reduce cost in energy storage systems.

EESAT2000 Conference: The ESS Program, under the sponsorship of the DOE, and in cooperation with the ESA, has taken over the responsibility for organizing the Electrical Energy Storage Systems Applications and Technology (EESAT) conference to be held September 18 to 20, 2000. The conference will be held in the Royal Plaza Hotel in the Disney World Resort, Lake Buena Vista, Florida. The international conference will address all aspects of energy storage system technologies including conventional and advanced batteries, supercapacitors, SMES, flywheels, CAES, pumped hydro, the power electronics and control systems, as well as system studies and economic analysis of storage systems. Individual components, system applications, and research into advanced systems and components will also be included in the conference agenda.

A call for papers was issued in September 1999, with abstracts due in January 2000. Technical and economic papers are encouraged. The component areas of interest include the energy storage system, power electronics, control and data acquisition. The application areas of interest include generation, transmission, distributed resources, distribution power quality, energy management, and customer applications. The research areas of interest include advanced systems and components, identification of the potential users and needs for energy storage and the future of the deregulated utility industry.

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2. Integration

Introduction

Under the Integration element, a strategy is being pursued to reduce the inefficient, one-of-a-kind system engineering that was historically required when an ESS is designed and built. A modular approach was recommended as the preferred method of achieving system flexibility and the lowest possible cost. The major subsystem components (storage, power conversion system [PCS], and controls) are designed as separate modules. This allows integration to take place either at the factory or at the user site. From a cost perspective, this modular approach permits more efficient engineering, design, and manufacturing processes to be used. Finally, the large quantity of on-site labor required to assemble and start up the system at the user site is minimized.

The Integration element consists of two subelements to fully address these system engineering needs. System development pursues development of complete, modular prototypes for end-use applications. Advanced battery systems, improvement of batteries in renewable systems, and integration of storage with village power supplies and at the substation level are major program initiatives. All are performed with industry under cost-sharing agreements. System evaluation focuses on collecting data in the field from working systems. The analysis and presentation of these data are crucial to development and verification processes necessary for new technology to be adopted. Systems, both large and small, from one end of the U.S. to the other, are being monitored and the data reported.

System Development

Advanced Battery Energy Storage System

The zinc/bromine battery is an emerging technology that has many attributes that make it attractive for energy storage applications. The main advantage of the zinc/bromine battery system is good gravimetric energy density, which results in a modular, transportable battery system with sufficient capacity to be placed anywhere on the utility grid. The battery is made almost entirely from plastic (high-density polyethylene), which makes it cost-competitive with lead-acid batteries at high-volume production without the hazardous manufacturing and recycling concerns. Also, the battery operates efficiently over a wide temperature range, functions under intermittent charge/discharge conditions, and can experience complete discharge hundreds of times without damage.

In 1997, ZBB Technologies, Inc. (ZBB), the ESS Program's industry partner on this project, participated in one of the largest turnkey advanced battery demonstrations in the United States. This major demonstration, a 100-kWh zinc/bromine battery system, was partially funded by the DOE/ESS Program and was completed at the ZBB test facility.

Following the completion of the 100-kWh battery tests in FY97, a new project was competitively placed with ZBB for the development and field testing of a 400-kWh advanced battery energy storage system (ABESS). Field testing a prototype, integrated ESS should enable ZBB to validate the technology and prove the reliability to the satisfaction of electric utilities and other users. Currently a demonstration is planned at a Detroit Edison site.

Status

The tasks completed in FY99 include:

- Preliminary design definition,
- Update to application analysis,
- Manufacturing cost study,
- Module network system testing,
- Qualification of a new module design, and
- Analysis of separators

System Design: The ABESS integrates three main components that comprise the storage system: the zinc/bromine battery, the PCS, and the necessary control equipment. The system has been configured to minimize transportation, installation, and maintenance costs. Once the system is located at the site, it can be connected to the utility grid by an overhead or underground service. The battery modules have been designed to allow for on-site maintenance and replacement of virtually any component in the battery module. The control system monitors all system parameters and shuts down the entire unit if any safety hazards arise. System operation parameters are collected and reviewed to resolve any unfavorable operating trends.

A schematic of the battery module is shown in Figure 2-1. The energy storage portion of the system

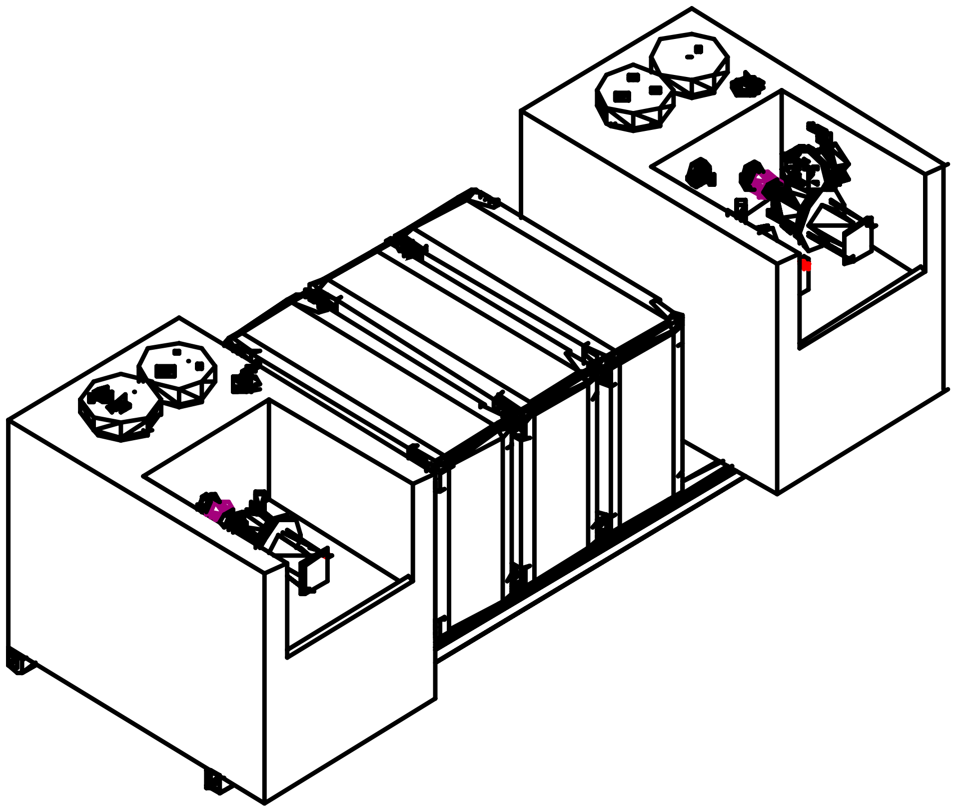
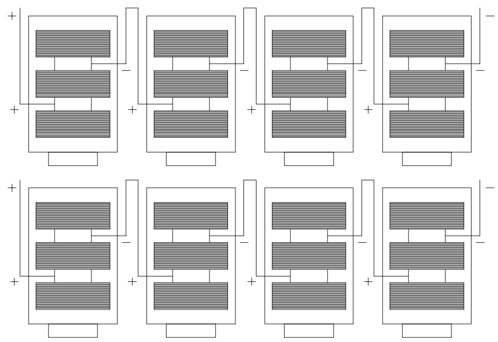


Figure 2-1. Schematic of 50-kWh Battery Module.

consists of eight battery modules, each containing three battery stacks connected electrically in parallel. Eight individual 50-kWh zinc/bromine battery modules each containing three battery stacks connected electrically in parallel supply the 400kWh. These modules are configured into two separate strings of four modules connected in series, with an open circuit voltage of 432 V (Figure 2-2). The two battery strings can be operated as two separate batteries or as a single battery, giving the entire energy storage system a great degree of charge/discharge flexibility. The battery system has a rating of 400 kWh at the two-hour discharge rate. Table 2-1 summarizes the 400-kWh zinc/bromine battery specifications.

The PCS converts the DC input from the batteries into three-phase, 480 Vac and is connected to a delta/wye isolation transformer. A 600-A fused disconnect is coupled to the transformer to manually isolate the entire storage system from the grid. The converter is a 200-kVA, three-phase, bi-directional, voltage-fed, current-controlled AC-DC electronic power conversion system. The PCS has a four-quadrant operation, meaning that it is capable of controlling its power factor while the battery is charging and discharging. A detailed specification for the PCS has been submitted to SNL and Detroit Edison. Table 2-2 summarizes the 200-kVA PCS unit specifications.

The ESS is controlled by two controllers–one controls the battery system and the other controls the PCS. The system programmable logic controller (PLC) is used to operate and monitor the two individual battery strings, each with its own "SYSTEM READY" signal. The PLC will coordinate the overall operation and safety of the system by comparing the measured parameters to preset limits. If the measured parameters fall outside the preset norms, the PLC will adjust variables, such as pump speed or heat exchanger pumps and fans (to control temperature). If the measured parameters cannot be modified to fall within acceptable limits, the PLC will generate either a FAULT or SHUTDOWN condition. If a fault condition should arise for one of the strings, that string would go into the "FAULT" mode, while the other string would continue undisturbed. If a potentially hazardous condition to the system and its surroundings is sensed by the monitoring system, the controller will completely shut down the system. Conditions that would result in a complete SHUTDOWN of the entire system include an electrolyte leak or elevated enclosure temperature.



String 1	Module
432-V O/C	108-V O/C
150-A nominal	150-A nominal
300-A continuous	300-A continuous

String 2	Total
432-V O/C	432-V O/C
150-A nominal	300-A nominal
300-A continuous	600-A continuous

Figure 2-2. Battery Module DC Interconnection Scheme.

Table 2-1. 400 kWh Zinc/Bromine Battery Summary Specifications

	Battery System	Module
DC interface	504 Vdc maximum	126 Vdc maximum
Capacity	400-kWh, 2-hr discharge	50-kWh, 2-hr discharge
Configuration	8 modules, 2 parallel strings of 4 modules in series	3 zinc/bromine battery stacks electrically connected in parallel
Dimensions	~ 8′ x 8′ x 20′	~ 8′ × 3′ × 3′
Weight	~ 40,000 lb.	~ 3,000 lb.

Table 2-2. PCS Summary Specifications

	PCS Unit Specification
Configuration	Modular, main PCS unit, filtering device cabinet and isolation transformer
Type	Three-phase, bi-directional, voltage fed bridge inverter
Continuous kVA rating	200 kVA @ 480 Vac
kVAR/kW rating	200 kVAR, 200 kW
Switching frequency	8 kHz
Short circuit AC	350-A continuous, 100-kA interrupting capacity
Short circuit DC	400-A continuous, 100-kA interrupting capacity
Efficiency	95% at full output
AC current distortion	5% maximum at full load
Power factor	Unity/controllable
Operator interface	External IBM compatible with Win95-based operator interface software

Normally, the system controller will monitor system parameters such as the operational mode of each string (i.e., charge, discharge, strip, standby, fault), string voltages and currents, ambient temperature, and enclosure temperature. In addition, the system controller maintains constant communication with the PCS. If either the PCS or the system controller detect a fault, the storage system (via the PCS contactors) will be disconnected from the utility grid. The controllers communicate with each other through relay closures represented as a SYSTEM READY signal from the battery and an ENABLE signal from the PCS. As long as these two signals remain active, the storage system will operate. Figure 2-3 depicts the relay communication between the PCS and the battery system controller.

Software, located on an optional data collection computer, will monitor the performance of the system. A program that polls specific PLC memory locations and stores this data in a file has been written. A computer is not necessary to run the system, but can be used to display real-time data on the computer screen via a RS232C serial line (between the PLC and the data collection computer). This information can be viewed off site, provided the appropriate modems are in place. The information compiled by the PLC for each of the eight modules includes parameters such as string voltage, stack currents, electrolyte levels, stack temperature, and reservoir temperatures.

Update to Applications Analysis: ZBB Technologies, Inc., envisions the zinc/bromine battery system as a distribution system peak-shaving device. The intended benefit is to defer conventional distribution system capacity upgrades. In addition, the system can address storage capacities over various dispatch schedules, power factor control, and reactive power (VAR) compensation. ZBB is conducting this applications analysis in partnership with the Detroit Edison Company.

The company has investigated several potential sites as locations for testing a 400-kWh zinc/bromine ABESS. They intend to demonstrate the transportability of the battery system by utilizing it for peak reduction and reactive supply on a summer peaking circuit, and for load-leveling and power-quality applications in the fall/winter period of the same year.

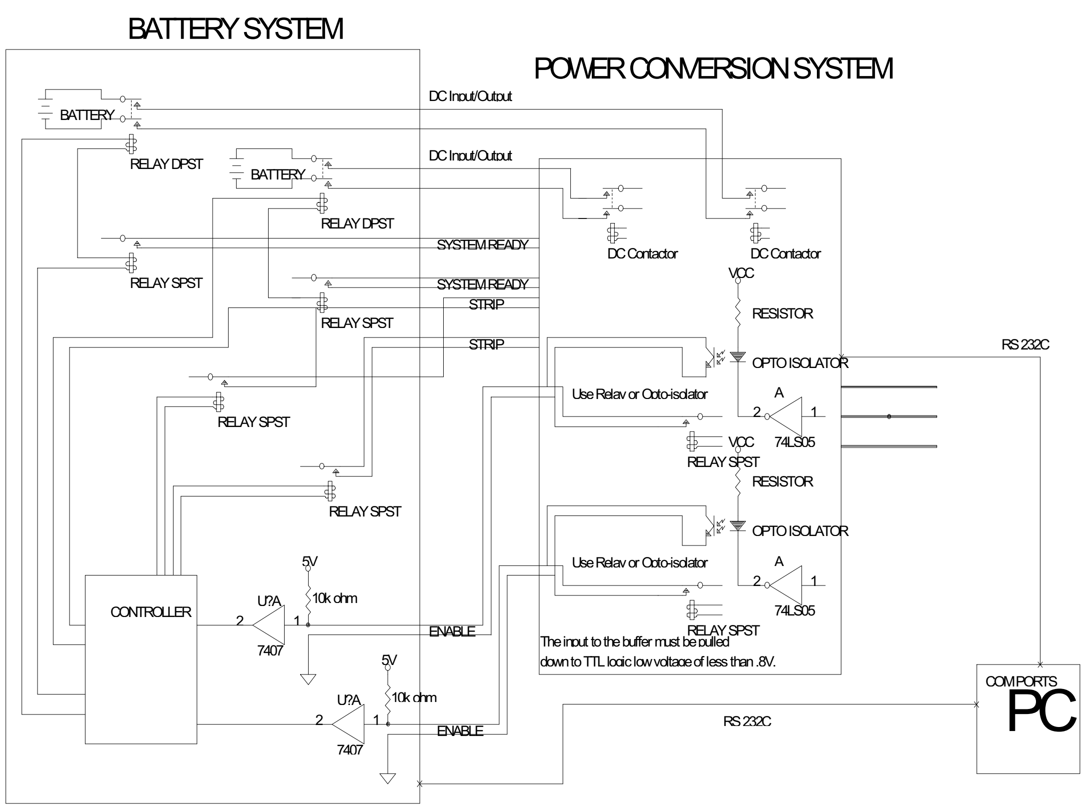


Figure 2-3. Connection between PCS and System Controller.

The first location under consideration for these applications is in the Lake St. Clair area, in the township of Harrison, Michigan, on the Beach Substation circuit load. The Beach circuit is temperature dependent due to its high concentration of residential and commercial air conditioning load.

The load profiles for this substation were evaluated over a one-week period from June 26 to July 1, 1998. The voltage profile remained fairly constant during the week, but large peaks were observed in the current profile. A peak in the current was observed every day, between the hours of 6 p.m. and 10 p.m. as seen in Table 2-3. The load profile during this one-week period is plotted in Figure 2-4.

The kVA values in Table 2-3 are plotted versus the daily peak temperature in Figure 2-5. The temperature data were obtained from the National Climatic Data Center (NOAA) for the city of Detroit, Michigan. Figure 2-4 demonstrates that the peak in the load is highly temperature dependent, which reflects how much AC load there is on the circuit.

The substation load profile in Figure 2-4 depicts the actual load that the substation observed during the seven days. This plot has some distinct peaks as well as dual peaks that could be shaved by an energy storage system. The 400-kWh system being built could not significantly impact the substation load profile; however it is reasonable to assume that there are points throughout the distribution system that have a similar load profile.

The 200-kVA/400-kWh energy storage system is suitable for an application near the load (as opposed to a larger substation load). Detroit Edison identified a potential site on the Beach circuit where customers have a low-voltage problem when there is a sufficient increase in ambient temperature. The Township of Harrison has experienced low-voltage problems and is located near the end of the circuit.

The potential site is a small municipal complex, which has an administrative office, city sewer and water department offices, and a police station. The power for this complex is supplied by a 4.8-kV three-phase circuit, of which a single-phase 4.8-kV line feeds a residential area. A potential location for the storage system has been identified in the parking lot in front of the administrative offices. The areas that are expected to benefit the most from an energy storage system installation are the administrative offices, the single-phase 4.8-kV residential line, and possibly the Sewer and Water Department offices.

The design load for the 4.8-kV circuit is 3.5 to 4.0 MVA. The location of the planned battery installation is far enough away from the substation where high load periods cause low-voltage problems. The timing of placement at this site may not work well, so data are currently being collected for a number of potential sites. The intention is to determine the most suitable location for testing the battery system during the summer of 2000. Circuits that are candidates for summer load relief and/or power quality applications include:

- STDF #4 (2628)–summer and winter loading at day-day rating,
- New Haven (312)– motor starting at the end load and voltage support,

Table 2-3. Beach Substation Distribution Circuit 2594 (Local 4.8 kV)

	Thursday 6/25/98	Friday 6/26/98	Saturday 6/27/98	Sunday 6/28/98	Monday 6/29/98	Tuesday 6/30/98
Peak temperature	96°F	91°F	80°F	88°F	88°F	78°F
Average temperature	84°F	81°F	75°F	78°F	78°F	71°F
Time of peak current	22:00	18:00	18:00	18:00	19:00	19:00
Voltage at peak	128	127	125	126	126.5	125
Chart reading	5.4	4.9	3.3	4.2	4.8	2.5
Current	648	588	396	504	576	300
Peak kVA	5746	4821	3429	4400	5048	2598

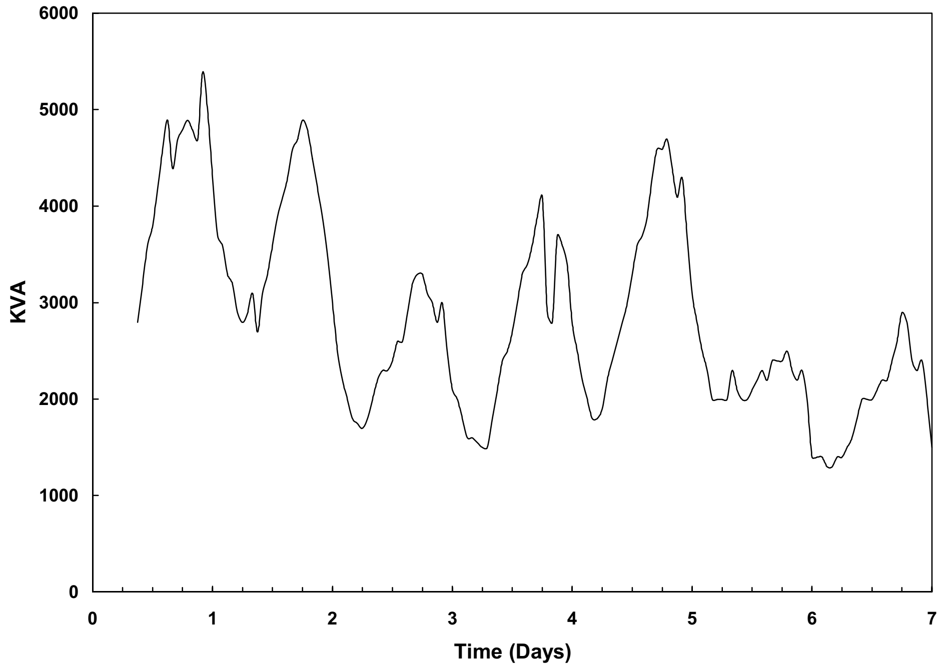


Figure 2-4. **Load Profile for Distribution Circuit 2594 for Beach Substation – June 26, 1998 to July 1, 1998.**

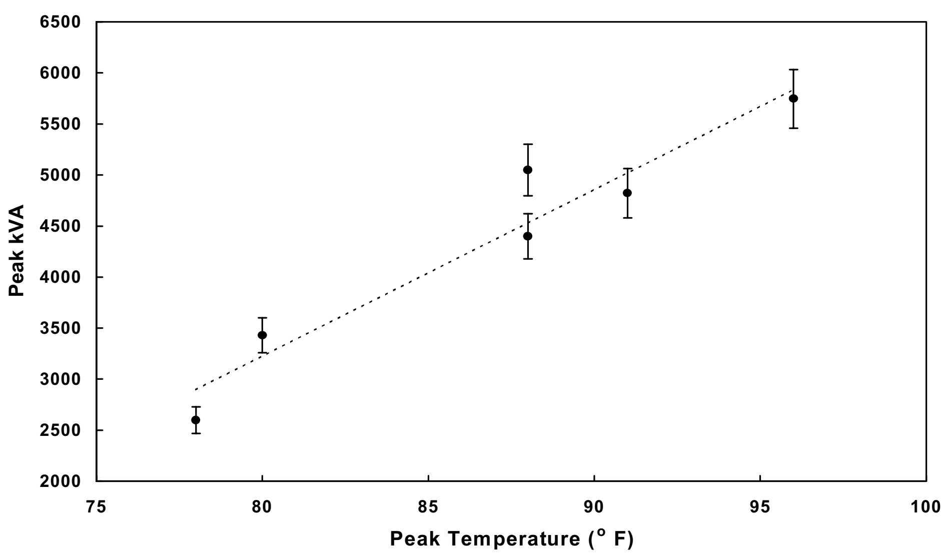


Figure 2-5. **The Effect of Temperature on kVA for the Beach Substation.**

- Richmond (8420)–Summer loading over day-day rating,

- Brewer (8840)–summer loading over day-day rating 200HP motor at the end.

General information for the candidate summer circuits is shown in Table 2-4. Load profiles for the Brewer circuit during June 1999 are shown in Figure 2-6. These circuits show peak in the load during the day. A location from the circuit selection shown below should provide an appropriate site for testing a 400-kWh zinc/bromine system.

The most promising candidate for the fall is a farm approximately 90 miles north of Detroit Edison's Macomb Center Headquarters on the Talbot Circuit in Palms, Michigan. This location has an established grain drying facility that services the drying needs of a number of farms in the area. Detroit Edison has encountered difficulty in reducing the amount of "flicker" from the grain drying facility at a reasonable cost to both Detroit Edison and the customer. The drying season generally runs from mid-September to the end of December. The analysis of this circuit is ongoing.

Cost Study: A detailed cost study was performed for the initial design of a 400-kWh zinc/bromine ABESS. Cost documentation was provided for material, labor and indirect cost to estimate the total cost of the system, including the PCS. The study also examined where cost reductions are necessary to improve the cost competitiveness of the system. The study estimated a cost of $646/kWh for a 400-kWh zinc/bromine battery system including labor and indirect costs. The cost including the power conditioning equipment was estimated at $963/kWh. A breakdown of the costs for a zinc/bromine battery system is given in Figure 2-7.

The PCS is a major portion of the total estimated cost of the 400-kWh system. The entire PCS cost is $316/kWh including the power unit, transformer, circuit breaker, and operating interface computer. The PCS for this system was custom designed, which caused the cost of the PCS to be over 30% of the entire system cost. Rapid advances in solid-state power switching devices, and anticipated benefits of mass production will reduce this cost considerably. Future prices for PCS systems are predicted to fall to in the range of $100/kWh.

The cost of the system container is $28K for one unit, and ~ $23K for ten units. This corresponds to a 17% reduction in price for a quantity discount. The container is another high-cost component of the zinc/bromine battery system, but it could also be considered as part of the balance of plant (BOP). The BOP for other battery technologies includes the building and support structures that would be included in the cost of the 400-kWh zinc/bromine battery system.

The total cost of the battery stacks ($104/kWh) will need to be reduced for this system to be cost effective. Some cost reductions will be realized when production numbers are increased, but this still will need to be further reduced. The most expensive component in the stacks is the separator material at about $48/kWh (nearly 50% of the cost of the stacks). The separator used in the zinc/bromine battery is very similar to lead-acid type separators, and should not cost significantly more than this type of material. The major raw materials used in the separator are polyethylene and silica, neither of which is extremely expensive, and extrusion of the material is also relatively low in cost. Lower cost separator materials will be an important part of reducing the cost of the battery system.

Table 2-4. Data for Summer Load Circuits

	Substation			
	STDF #4	New Haven	Richmond	Brewer
Circuit	2628	312	8420	8840
Circuit Voltage (kV)	4.8	4.8	13.2	13.2
Peak Loading (kVA)	21.6	60	51	140
Rating (kVA)	1,200	3,200	8,700	7,700
Number of residential customers	239	1,124	1,648	2,347
Number of industrial customers	19	94	271	167

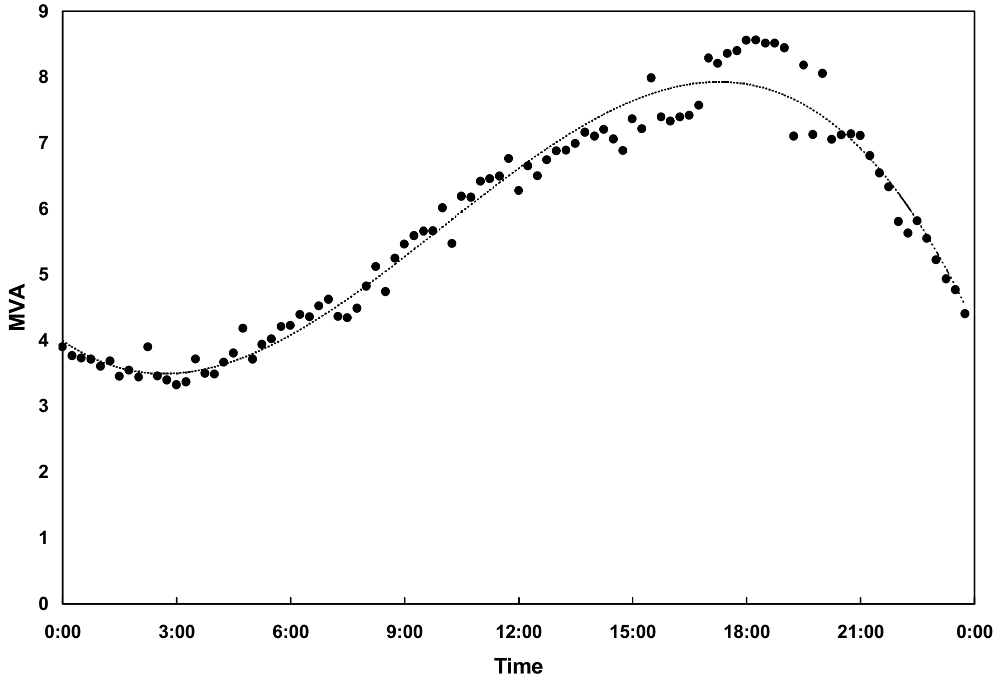


Figure 2-6. Load Profile for Brewer Circuit during June 1999.

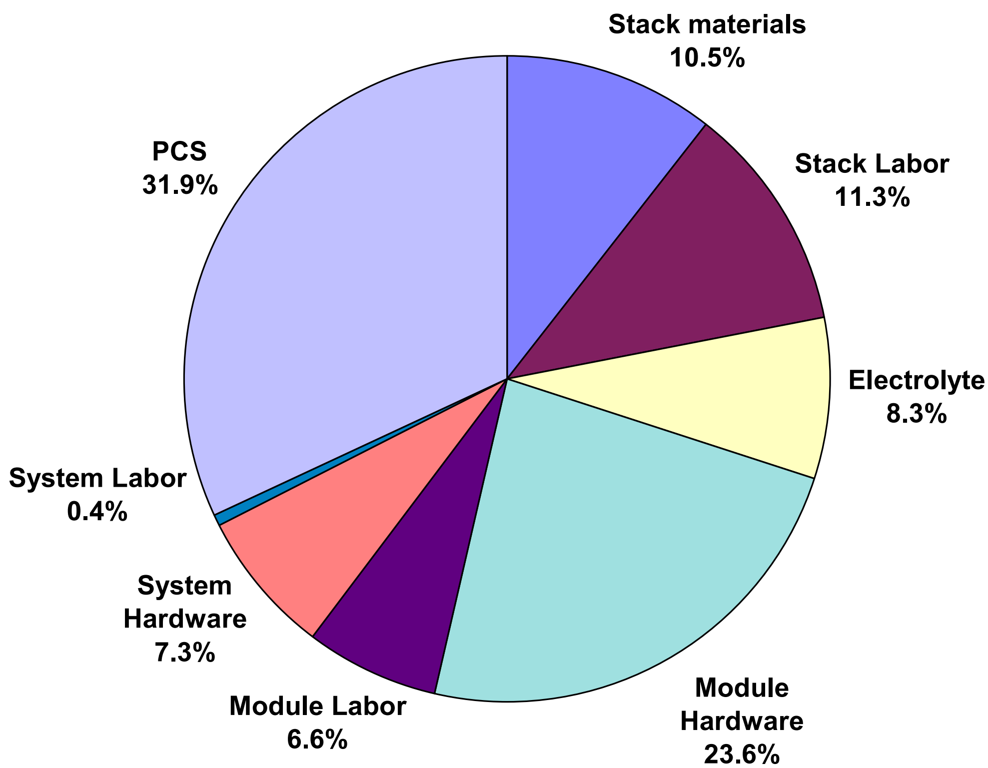


Figure 2-7. Cost Breakdown for 400-kWh Zinc/Bromine ABESS.

The other expensive components in the battery stacks include the injection-molded parts: endblocks, covers, and flow frames. The cost of these will be reduced significantly when manufacturing numbers are increased. Also, a number of alternate injection molders are investigating ways of reducing the cost of manufacturing these components.

The components of the electrolyte are estimated to cost $82/kWh. The cost of this will be drastically reduced when economies of scale are realized. The zinc bromide solution costs would be reduced from $4/kg to $3/kg in large volumes, a reduction of 26%. The bromide complexing agent in the electrolyte, which is specifically manufactured for the Zinc/Bromine battery, is very expensive at $20/kg in small quantities. When quantities of this material are increased, the complexing agent could be reduced by over 90% to about $2/kg. The remaining chemicals in the electrolyte solution would also see some degree of cost reductions with economies of scale. Scaled-up production of the Zinc/Bromine battery electrolyte would reduce the total cost of the electrolyte for a 400 kWh battery system by a total amount of nearly 80%.

At this time, the drive motors for the pumps are specially manufactured for the zinc/bromine system, at a cost of $500/motor. For high volume quantities, the 1/2 HP motors would cost $186 and the 3/4 HP motors would cost $219 a piece. This corresponds to a savings of $876 per module, and $7K/400-kWh system, or a 58% reduction in the total cost of the drive motors.

Cost reductions observed for increased quantities were only included for some of the major components of the system. The cost for all components would also be reduced somewhat when scaling up production of the system. By examining the major cost reductions mentioned, the cost of the 400-kWh battery system (not including the PCS, labor or indirect costs) could be reduced from $466/kWh to $392/kWh, nearly a 16% decrease in cost.

Additional reductions are predicted for the labor costs. This will be especially evident in the manufacturing of stacks and the assembly of modules as the product moves into commercial production. A greater percentage of the manufacturing labor will become technical and workshop manpower, at labor rates substantially less than the professionally qualified development engineers now engaged in the manufacturing of battery systems. The ratio of technical or non-specialized labor to professional labor will increase as manufacturing processes are stabilized into high volume, repetitive processes.

Module Network System Testing: A critical design iteration in the control system for the zinc/bromine battery will be its ability to function without utility power. To demonstrate this feature, a 50-kWh module was tested without utility power. This strategy will simplify the design of the control for the battery system by enabling it to function in an uninterruptible power supply (UPS) or as a remote area power supply (RAPS).

A commercially available isolated DC/DC converter was used to convert the battery voltage to 26 Vdc to run the control system. An additional DC/DC converter was designed and assembled by ZBB to supply the input voltages needed to run the input/output (I/O) board. A smoothing capacitor coming directly from the battery stacks runs the motor controllers. This was easily done because the motor controllers have built-in isolation, which isolates the control section from the battery voltage. The motor controllers operated without interruption from the battery stacks until the battery voltage decreased to below about 30 V. Three small 8-V lead-acid batteries were connected in series to supply 24 V to power the control system after the battery voltage became too low. This was needed to maintain control functions during the strip portion of the discharge, to keep the system active, and so that the Keyence programmable logic controllers would not need to be reset after each discharge. A diode was used to allow the control system to run from the battery supply (zinc/bromine or lead/acid) with the higher voltage. This ensured that all power for the control system was taken from the zinc/bromine battery during the charge or discharge phases of the test cycles, with only minimal use of the backup power supply during the strip phase. For this exercise, the lead-acid batteries were not charged during each cycle. For an actual stand-alone or RAPS system, a simple trickle charging of the backup power supply would need to be considered.

The battery system was also run with the control system and motor controllers running from AC power for comparison purposes. The performance data with the controls running off the battery stacks are compared to those with the controls running off of AC power in Table 2-5 indicates that the amount of energy used by the control system and pumps is 3.8 kWh for a 50-kWh discharge. The fact that this number is less than 10% of the energy generated indicates that this system can be used without utility power.

Table 2-5. Performance of 50-kWh Zinc/Bromine Battery With and Without the Control System and Pumps Powered by the Battery Stacks

	Controls and Pumps Powered by Battery	Controls and Pumps Powered by AC Power
Discharge time (minutes)	209.9	224.8
A-hours	524.6	562.0
Energy (kWh)	49.47	53.27
Coulombic efficiency	77.7%	83.3%
Voltaic efficiency	83.0%	83.2%
Energy efficiency	64.5%	69.3%

Qualify New Test Modules: Tests are being conducted to verify performance improvements and to evaluate the impact of lower cost components. A number of changes in the original module design have been implemented, either to improve the performance of the module, or to examine the use of lower cost components. Several of the changes that were made in order to improve either performance or cost include:

- Use of larger pumps to increase the rate of electrolyte flow through the battery stacks.
- Change in plumbing configuration to improve the flow of electrolyte through the battery stacks.
- Repair of the control system to improve the control of the levels in the electrolyte reservoirs.
- Use of a prefabricated manifold plumbing system that is lower cost and easier to manufacture.
- Testing of a new reversing valve design that is lower cost and easier to manufacture.

The improved performance achieved with the various changes is shown in Table 2-6.

With the modifications made to the 50-kWh battery module, the performance increased from about 61% to 70% energy efficiency. With anticipated improvements in separator material, which will be discussed in the following section, the 50-kWh zinc/bromine battery module is expected to achieve greater than 75% energy efficiency.

Separator Analysis: The separator material used in the zinc/bromine battery is one of the critical components of the battery. The important properties of the separator include the bromine diffusion rate and the resistance, both of which will have an effect on the energy efficiency of the battery. The bromine diffusion gives an indication of how much self-discharge the battery will encounter. The resistance of the separator affects the voltaic efficiency of the battery.

The most recent shipment of separator material from the vendor was found to have a very similar bromine diffusion rate to that of previously obtained materials, but the resistance was approximately double that of the earlier materials. This increased resistance resulted in a reduction of 5 to 6% in energy efficiency when assembled into a battery. An in-depth analysis was performed to determine the differences

Table 2-6. Effect of Module Modifications on Performance

Modification	Coulombic	Voltaic	Energy Efficiency
None	77.1%	79.6%	61.3%
Larger Pumps	82.9%	78.6%	65.1%
Changed Plumbing	82.5%	82.7%	68.2%
Repaired Controls	83.3%	83.2%	69.3%
Manifold System	84.2%	83.0%	69.8%
Reversing Valve	84.0%	83.2%	69.8%

between the two separator materials, and to examine how the material can be improved in the future. The tests performed included themogravimetric analysis (TGA), X-ray photoelectron spectroscopy (XPS), scanning electron microscopy (SEM) and X-ray diffraction (XRD).

XPS examined the elemental composition of the surface materials, revealing a difference in the level of silica exposed at the very surface of the two membranes as shown in Table 2-7. The high-resistance separator material has a much lower percentage of silica at the surface than the standard material, which would cause the material to be more hydrophobic. Since the electrolyte is a water-based solution, this could be the cause of the high resistance of the separator.

Table 2-7. X-ray Spectroscopy Results for Separator Materials

	Standard Material	High Resistance Material
Carbon (C)	39.4%	70.4%
Oxygen (O)	41.4%	30.0%
Silica (Si)	19.2%	9.6%

The reason for this difference in relative level of organic material to silica ratio is clearly explained by the microstructural differences found with the SEM. A direct comparison of the SEM images shows that the coated silica particles are less distinguishable on the surface of the high resistance membrane because of a higher level of polymer matrix.

XRD provides a measure of the crystallinity of the material. The XRD traces show two strong diffraction peaks between 20 and 25º that are indicative of polymers containing CH_2 chains (e.g., paraffin, polyethylene). The intensities of the peaks show the polymers in both materials to be crystalline. The strong diffraction peaks from the polymers are underlined by a diffuse background that has a broad peak in the range 15 to 30º and indicates the presence of amorphous material in the sample. This amorphous material will comprise non-crystalline polymer material and amorphous silica. The differences in the XRD traces from the two samples show that the diffraction peaks from the well-crystalline polymer component of the standard sample are less intense than the corresponding diffraction peaks of the high-resistance sample. This indicates that the content of well-crystalline polymer material is lower in the standard sample than in the high-resistance sample. The inference from this observation is that there is relatively more amorphous (silica) material in the standard material than in the high-resistance sample.

When considering the XRD results, it should be remembered that XRD does not compare equal masses of sample but approximately equal volumes of sample. It is therefore possible that the XRD results indicate that the standard material is more porous than the high-resistance material.

All three of the analytical tests indicate that the standard separator material contains a higher concentration of silica at the surface than the high-resistance material. It was confirmed that the vendor made a slight variation in the separator formulation, which appears to have caused the material to be high in resistance. The vendor has stated that the original formulation will be used for manufacturing any separator material in the future.

Alternate Renewable Generation and Storage System Designs to Improve Battery Performance

An investigation of alternative configurations to optimally use lead-acid batteries in renewable hybrid systems began in the third quarter of FY98. The purpose of this project is to devise systems for renewable hybrid installations that will improve the performance of the lead-acid batteries used in these systems. “Configuration” refers to the electrical arrangement of the major components of renewable hybrid systems such as the photovoltaic (PV) and/or wind generator, diesel generator, storage (for example, batteries), and the power conversion subsystem. Improving the performance of the lead-acid batteries will extend the battery life cycle costs.

The goal of this work is to devise and develop alternative configurations for the lead-acid batteries in renewable generation and storage (RGS) systems so that capital, operating and maintenance (O&M), and repair and replacement costs might all be reduced. Specifically, Electrochemical Engineering Consultants, Inc. (EECI), in association with SNL, is seeking to develop battery energy storage (BES) subsystems for PV hybrid RGS systems that offer the potential for reduced life cycle costs. Under a previous contract, two families of alternative configurations had been conceptualized and outlined, one directed toward equalization and the other toward the control of battery charging. The analyses from this work indicated that the alternative configurations that had been devised might ultimately lead to lower life cycle costs. In the work currently being conducted, "breadboard" versions of one of the alternative configurations devised in the first phase of work will be developed and tested to provide a firmer foundation on which to perform further cost/benefit analyses. Thus, this phase of work involved the following tasks:

- Selecting the alternative configuration for further development using ongoing analyses with a model developed previously as the basis for making the selection.
- Selecting and acquiring hardware for the alternative configuration to be tested.
- Writing and testing the first software version that will monitor and control the hardware of the alternative configuration to be tested.
- Development work on the breadboard hardware that constituted the test set-up for this phase of the work.
- Building increasingly sophisticated versions of the breadboard hardware.
- Testing successive versions of the breadboard hardware in an automated cycling mode, such automated cycling being controlled by the software that was developed.
- Performing analyses of the testing performed to verify that the goals of the project were being met.

Status

The effort during FY99 involved building increasingly sophisticated versions of the breadboard hardware and then testing this hardware with more fully developed versions of the software required for its operation. When the breadboard was first developed, testing could only be performed with cycles at a shallow depth of discharge (DOD). As the development progressed however, it was necessary to test with cycles of 50% DOD, so that the development would more closely mimic lead-acid batteries in the field.

During the first quarter, it was decided that the alternative configuration would be the most appropriate choice to develop because it allows "smart" control of both bulk charging and of equalization. Also in the first quarter, it was decided that "off-the-shelf" components should be used wherever possible and that these components should mimic those used in presently available solar hybrid systems. Therefore, the following components were acquired for the breadboard testing:

- Trojan T-105 (6-V, 225-Ah) flooded lead-acid batteries, which are used extensively by solar hybrid system suppliers;
- Several automotive battery chargers;
- Several "modified sine wave" type DC-to-AC inverters;
- Twelve power resistors providing a load capability in total of more than approximately 50 A at 12 V; and
- Ancillary equipment required to complete the system.

Additional accomplishments in the first quarter include writing the first version of the software for control of the alternative configuration and developing and testing the DAS.

In the second quarter of FY99, assembly of the breadboard setup for testing the alternative configuration was initiated. In its most basic form, the alternative configuration test setup consists of the following:

- A battery comprised of two parallel strings each with two T-105 modules in series,
- A 40-A, 12-V battery charger,
- A 0.5F capacitor bank to partially smooth the "full-wave rectified" current from the charger,
- An approximately 0.4-ohm resistor bank for discharge,
- Various other control circuits, low-wattage power supplies, and cooling devices, and
- A "486" class PC equipped with a digital/analog (D/A) board for data acquisition.

The entire setup is controlled with the PC, using software written specifically for this purpose. The data needed to determine the performance of the alternative configuration under test is stored on the hard drive of the PC, pending later analysis. During the second quarter, many technical issues with the test setup had to be resolved before testing could begin. Heat build-up in linear power supplies, excessive ripple on the charge current, instabilities leading to oscillation in the control circuits had to be controlled, and refinements were made to the control software. By the middle of the second quarter, the test set-up was operating satisfactorily.

The alternative configuration system became operational in the later part of the second quarter and the remainder of FY99, was operating more or less continuously. Operation during this time consisted of automated cycling with discharges and bulk charges, each lasting approximately seven hours. In the last few weeks of FY99, the cycling was continuous, under automated control, with few interruptions for week-long periods. The only interruptions that occurred were operator-initiated.

The modeling that was performed during the first phase of the work in FY98 showed the alternative configurations that had been conceptualized had promise to reduce the O&M costs for solar hybrid systems. An analysis of the data from the testing that has been performed confirms the results of the modeling. In addition, the testing allowed conceptualization of several other ways in which to lower costs of operation, and perhaps lower capital costs for solar hybrid systems in the future.

Small Village Storage System Integration

Chugach Electric Cooperative and the State of Alaska Energy Authority have proposed a collaboration with the ESS Program to design, build, and demonstrate a 20- to 30-kW energy system for small Alaskan villages. The purpose of this integration, test, and field evaluation project is to quantify the benefits of battery storage for small villages that have diesel-only generation. This study will collaborate with a similar study planned by the U.S. Agency for International Development. The detailed system design will be initiated in FY99. If appropriate, a prototype system will be assembled and undergo initial testing and debugging at a test bed in Anchorage under controlled conditions. Following the successful completion of this phase, the prototype system will be moved to a village site selected by the Alaska partners. The system will be operated at the site to generate data that will support the analysis necessary to quantify the benefits of storage under these operating conditions. The ESS Program expects to share the cost of about a third of the total project, with the remaining costs being shared between Chugach Electric and the Alaska Energy Authority.

The feasibility and system design study was initiated in June 1999. A contract was placed with Sentech, Inc., to conduct the study and prepare a report describing the results. A spreadsheet model will be developed and used to analyze operating data from representative sites in Alaska. The net benefit of the battery to the overall power system will be determined, along with a parametric study of component sizes and operating strategies.

Status

The SNL and Sentech study team visited Alaska and had discussions with the director and staff of the Alaska Energy Authority, with Chugach Electric Cooperative staff and management, and with Alaska Village Electric Cooperative (AVEC) personnel. The perspectives of each organization were obtained, and there was strong support for the project. The objectives of the Alaskan organizations for this project are to save diesel fuel and associated costs, reduce pollution and environmental threats from fuel transportation and storage, and improve the economic conditions of the more than 200 remote communities in Alaska. Each organization provided the study team with invaluable data on the remote power systems in Alaska, on diesel generation performance and operation, and on the conditions of fuel transportation and storage. A database was developed by a SNL summer student from Metlakatla, Alaska, which characterizes most of the remote power systems and communities in Alaska.

To analyze the potential of BES systems in remote villages, the study team first obtained actual load data from several off-grid Alaskan villages. Based on summary data of installed generating capacity from the Alaska Energy Authority, the analysts classified villages into three categories: small, medium, and large (corresponding to less than 1 MW, between 1 and 10 MW, and greater than 10 MW of generating capacity). Working with officials in the Alaska Energy Authority and local utilities (in particular, Chugach Electric Association and the AVEC), the analysts identified representative villages with available load data. After site visits and discussions with operating personnel, further analysis was performed on the data collected from Chistochina, Alaska, (representing a small village) and Selawik, Alaska, (representing a medium village).

In order to minimize system cost, initial analyses were conducted making use of existing generating equipment. Using current configurations and common operating procedures in Alaskan villages, the study developed two operating regimes for incorporating BES into the village power supply. The first uses the storage system as a peak-shaving/load-leveling device. The diesel is run constantly, but it is run at a more efficient full loading. The BESS discharges during the peak hours, meeting the load demand and recharges during the off-peak hours. The second regime uses the storage system to provide full village power during off-peak hours. The diesel only runs during peak hours and any additional time that is needed to recharge the battery. Under this system, the diesel also runs fully loaded, but incurs fewer operating hours and has more start/stop cycles.

Based on preliminary modeling, the analysts decided that the first operating regime (peak-shaving/ load-leveling, also referred to as "power smoothing") produced substantially higher fuel savings than the second operating regime (referred to as "cycle-charging"). Additional analysis of the power-smoothing regime indicates that the largest fuel savings occur in smaller villages with lower baseline fuel efficiencies and higher fuel costs. The study indicates that Chistochina could save approximately 12% in fuel consumption for each month the system is in operation. Larger villages, including both "medium" and "large" villages as defined for this study, take advantage of larger, more efficient diesel gensets and have a larger, more diverse load base, allowing for increased constant loading of the existing diesels (absent significant industrial loads). Hence the study indicates fuel savings in Selawik of only 6%. Economic analyses indicate that reducing BES system capital costs will increase the market opportunities of these systems to more villages.

The approach to data collection was to obtain diesel generator and system operating performance data for common units used in remote U.S. villages. Numerous reports were reviewed from Alaskan Village Power Systems, DOE, and SNL. The study team contacted the Alaskan Energy Authority, the AVEC, and Chugach Electric Cooperative to identify appropriate sites for data collection. Based on an initial review of Alaskan generation data and telephone consultations, the analysts identified three sites from which to collect data. The site evaluation was based on several criteria including diesel fuel cost, site location, availability of operating system data, diesel capacity, and operational history and fuel consumption. The sites evaluated for the study, corresponding to small, medium, large and multi-generating units, were Chistochina, Selawik, and Kotzebue. Details on these sites are presented in Table 2-8. The map shown in Figure 2-8 illustrates the location of the selected villages relative to other major cities and villages in Alaska. Kotzebue was eliminated from the study because the low cost of electricity there would not support battery storage implementation for this application alone.

Site visits were conducted from June 28, 1999, through July 2, 1999, to obtain comprehensive field data. Meetings with AVEC, Chugach Electric Cooperative, and local site operators were held to discuss the overall scope of the project and to get support for the data collection effort. The analysts then reviewed all data obtained and compiled the data into appropriate Excel spreadsheet files. Based on discussions with the Alaskan utility operators, the analysts developed two battery/diesel-operating scenarios to model system operation performance. The analysts then contacted diesel generator manufacturers, including John Deere, Caterpillar, Cummins-Onan, and Detroit Diesel, to obtain manufacturer genset operating specifications. Battery and PCS manufacturers were also contacted to obtain price and performance data on those systems. These manufacturers include GNB Technologies, C&D Technologies, Exide, and Applied Power.

Diesel/Battery Hybrid Model Results

The battery system for each village was specified based on the gross power and energy requirements of the village and available hardware. The battery specifications were then refined based on iterative runs of the model, until performance parameters were "optimized." The battery system proposed for Chistochina consists of a single string of 40 6-V cells, each cell having a nominal capacity of 300 Ah. This produces a battery system

Table 2-8. Alaskan Village Diesel System General Overview– Evaluation Results

Generating System Size	Capacity	Village	Electricity Rate (cents/kWh)*	Avg. Fuel Price ($/Gal)
Small	160 kW	Chistochina	36.8	.83
Medium	1571 kW	Selawik	46.6	1.63
Large	11,180 kW	Kotzebue	21.8	.85

– Rate before applying power cost equalization subsidy.

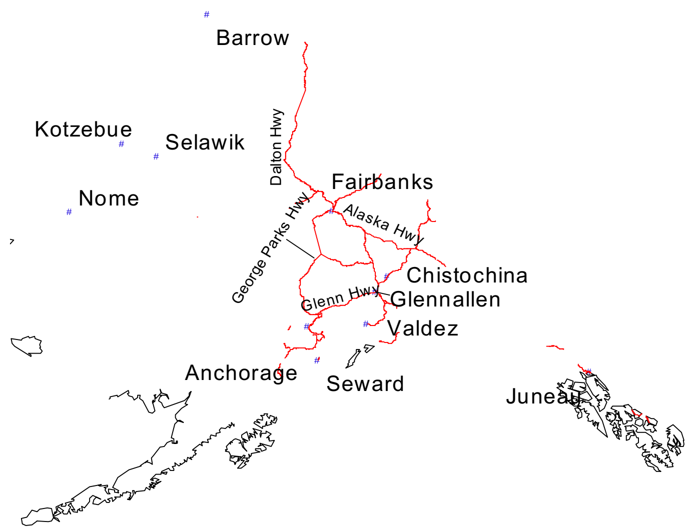


Figure 2-8. Regional Map Showing the Three Selected Villages Relative to Other Major Cities and Villages in Alaska.

with a potential of 240 Vdc and 72 kWh of energy storage. A quick review of available marketing literature confirms the availability of lead-acid batteries meeting these general specifications (that is, capable of forming a 240-Vdc, 72-kWh battery pack, although particular cell configuration may not exactly match the modeled system). The PCS was modeled as being 95% efficient on the inverter end and 95% efficient on the rectifier end, which is consistent with commercially available, state-of-the-art PCS.*

The proposed Selawik battery system consists of eight parallel strings, each containing 120 serially connected 2-V, 1500-Ah cells. This results in a 12,000-Ah battery, with 2,880 kWh of energy storage, also operating at 240 Vdc. Once again, commercially available products can be configured to meet this specification. The PCS for Selawik was also modeled at 95% efficiency for both the inverter and rectifier. Table 2-9 summarizes the BESSs that were modeled.

Preliminary runs using the National Renewable Energy Laboratory's (NREL's) Hybrid2 model indicated substantially greater fuel savings using a power-smoothing approach as compared to a cycle-charge approach. Therefore, given resource and time constraints of the current study, modeling efforts were focused on further study of this power-smoothing configuration.

Table 2-9. Summary of BESSs That Were Modeled

	Chistochina	Selawik
Cell capacity (Ah)	300	1500
Cell potential (V)	6	2
Cells in series	40	120
Strings in parallel	1	8
Battery storage (kWh @ 1-hr rate)	72	2880
PCS efficiency (%)	95	95

Figure 2-9 shows the performance characteristics of one week of operation of the Chistochina system as predicted by the model. In this system, the battery is generally kept at a fairly high state of charge (SOC). However, the diesel does not have a substantial leveling of its load. This is expected, as the BESS is primarily used as a peak-shaving system.

Using manufacturer's specified fuel consumption curves, the simulated fuel efficiency of the baseline case (diesel only) is substantially better than the overall fuel efficiency reported in Chistochina in the Power Cost Equalization (PCE) report** (12 kWh/gal vs. 10 kWh/gal). Therefore, the fuel consumption curves were adjusted to more closely match the observed fuel

* Atcitty, S., S. J. Ranade and A. Gray-Fenner. *Summary of State-of-the-Art Power Conversion Systems for Energy Storage Applications*. SAND98-2019. SNL. September, 1998.

** Alaskan Division of Energy. *Statistical Report of the Power Cost Equalization Program*, Ninth Edition, 1998.

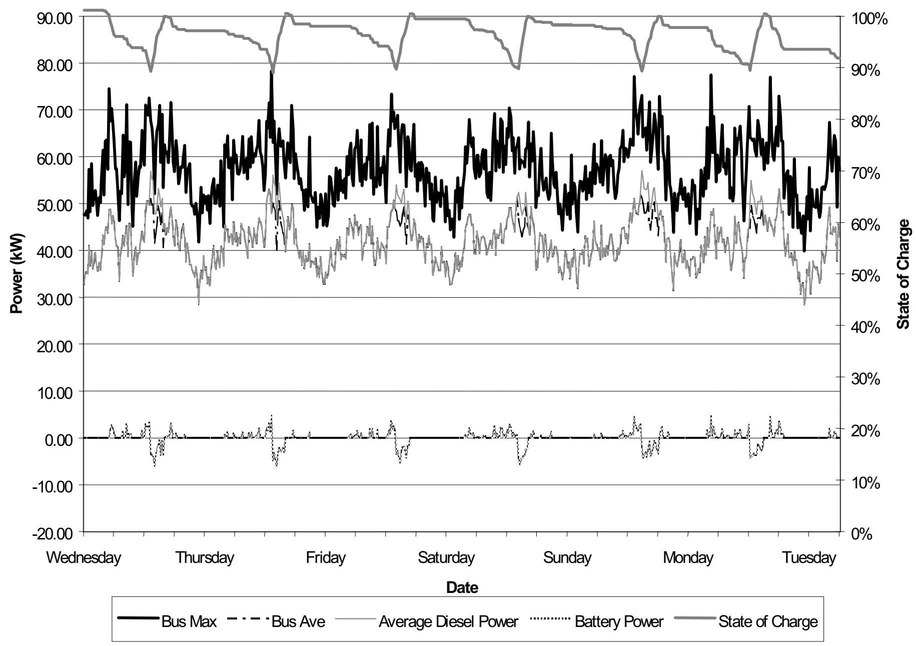


Figure 2-9. Chistochina Power Smoothing Fall and Winter.

efficiencies. Using this adjusted fuel consumption, the ESS has fuel savings of 12% over a one-month fall and winter power system simulation (using data extrapolated from the two-week data collection effort). The fuel savings results from using a smaller engine (60 kW) coupled with the energy storage instead of the larger engine normally used in the fall and winter months. The smaller engine runs at higher loading factors than the larger engine, and thus operates in a more efficient range. The savings occur despite losses arising from the ESS of around 40% (that is, the ESS operates at 60% efficiency), and the lower baseline efficiency of the smaller genset.

The 1996 average fuel cost for Chistochina was $0.78/gal including the PCE. Extrapolating the one-month simulation over a nine-month period (the period during which the larger genset usually runs in the village), the village will save about $2.5K per year in fuel costs. In a similarly sized, more remote village fuel costs could easily double to $1.60/gal due to location and restricted access to the Alaskan highway system. In this case, fuel savings would total approximately $5K per year.

To obtain real-world price information for this system, the analysts contacted several battery manufactures, and were, in turn, referred to affiliated system integrators for quotes on systems closely matching the system specifications for Chistochina. Based on the best match provided by the vendors, a system similar to the one simulated for Chistochina could cost approximately $60K.* This includes approximately $30K for the PCS and $30K for the battery. With enough units sold, the cost of a PCS for the system studied here could be expected to approach the uninterruptible power supply (UPS) power electronics cost based on the quotes from affiliated system integrators. An independent SNL study of PCS costs indicates that PCS units for off-grid applications range in cost from $200 to $1200/kW, with modest expectations of price reductions in the near-term (2- to 5-year time horizon).** Table 2-10 summarizes the current, quoted price for similar equipment, as well as projected future costs for these systems.

In a village with low fuel costs such as Chistochina, the simple payback period for the system would be approximately 15 years. However, in a more remote village with double the fuel cost, the simple payback period for the system would approximately match the expected replacement period for the battery. In this case, the system would just break even compared with the baseline system. Note that these calculations do not assume the purchase or maintenance of a diesel genset (since this component already exists). Adequate data correlating diesel maintenance costs with engine

* Powerware Plus 160 Model 130, rated at 160 kVA: $32,300 for UPS electronics. Include 240 cells of C&D XT3KC-11 batteries (40 kW for 2 hours or 105 kW for 45 minutes) for an additional $31,750.

** Atcitty, op. cit.

Table 2-10. Summary of Current Quoted Price for Similar Equipment, and Projected Future Costs for Systems at Chistochina

Item	Quoted Price	Future Range
Flooded Lead-Acid Battery	$750/kW*	$275-350/kW**
Power Conversion Equipment	$190/kW*	$175-1000/kW†

* Powerware Plus 160 Model 130, rated at 160 kVA, see footn ote at bottom of page 2-16.
**EPRI, U.S. DOE. *Renewable Energy Technology Characterizations.* December 1997. Appendix A.
† Atcitty, S., S. Ranade & A. Gray-Fenner. *Summary of State-of-the-Art Power Conversion Systems for Energy Storage Applications.* SAND98-2019. SNL. September 1998.

loading factors was not obtained, and thus this aspect of the system could not be adequately modeled. If operating the diesel at full load decreases maintenance costs (such as through more complete combustion and less fouling of the injectors), this would improve the economics of the modeled system.

In the Chistochina simulation, the ESS serves as a "peak shaver." That is, it operates for a few minutes out of each hour (during peak hours) to cover highly transient loads above the rated capacity of the diesel. Using the same dispatch method (power smoothing), the system could also be run as a "load leveler," where the ESS would cover the average system peak, which occurs several hours each day. Converting the Chistochina system from a peak-shaver to a load-leveler would require substituting a 45-kW genset for the 60-kW genset already in place. However, analysis of such a system does not indicate additional fuel savings for the village when running in this mode. Although operating in a load-leveling mode improves diesel loading, as shown in Figure 2-10, it does so at the cost of cycling more energy through the battery. The gain in efficiency from improved diesel loading is not enough to offset the additional energy losses from the ESS. Furthermore, running in this mode tends to shorten the battery life expectancy (from deeper discharges), thus making the economic case less attractive.

With peak system loads five times greater than those of Chistochina, Selawik offers a substantially different test case. The average winter load in Selawik is about 340 kW (based on January sample data). This provides a good match to the existing 350-kW diesel gensets already installed in the village for the purposes of "load leveling" (as compared to the "peak shaving" achieved in Chistochina). In this case, a 350-kW genset is paired with 2.8 MWh of BES to cover the same load served by the 557 kW genset.

Figure 2-11 shows the modeled system performance for one sample week in Selawik. In this system, the battery undergoes very deep and somewhat irregular cycling. As is typical in Selawik (based on an analysis of the full two months of data obtained), peak loads are highest during the beginning of the week, trailing off toward a notable low during the weekend. Thus the battery is quickly drained on Monday, and is only able to partially recharge before discharging again Tuesday, although to a much lower depth. The maximum state-of-charge gradually increases during the week, and the battery is fully recharged on the weekend. This system, however, allows the diesel to operate at an optimal flat-out maximum level through the entire workweek, only going into load-following mode on the weekend when the battery is fully charged.

When using manufacturer-specified fuel consumption curves, the system does not provide net fuel savings. However, as in Chistochina, the observed* village heat rate of 10.8 kWh/gal falls substantially short of the 14.4-kWh/gal heat rate predicted by the model. When the heat rate curves are adjusted to more closely match the 10.8 kWh/gal observed village value, fuel savings increase to around 6%. At $1.00/gal, this translates into $15,000/year in fuel savings cost. In addition, the village can reduce on-site fuel storage requirements by 15,000 gallons. Note that the 10.8-kWh/gal observed village heat rate was reported for the period of July 1, 1995 through June 30, 1996. This was before the installation in June 1996 and June 1997 of the 557-kW (the baseline units used in this analysis) and 315-kW generating units in Selawik. AVEC reports that since this installation, fuel consumption in Selawik has improved to much closer to the 14.4-kWh/gal, which was calculated in the model. Therefore, it is unlikely that the modeled system would provide fuel savings benefits in Selawik with the current generating capacity.

Table 2-11 summarizes the results from the three analyses conducted for this report (Chistochina System A, using a battery energy storage system to eliminate

* Alaskan Division of Energy, *op cit*.

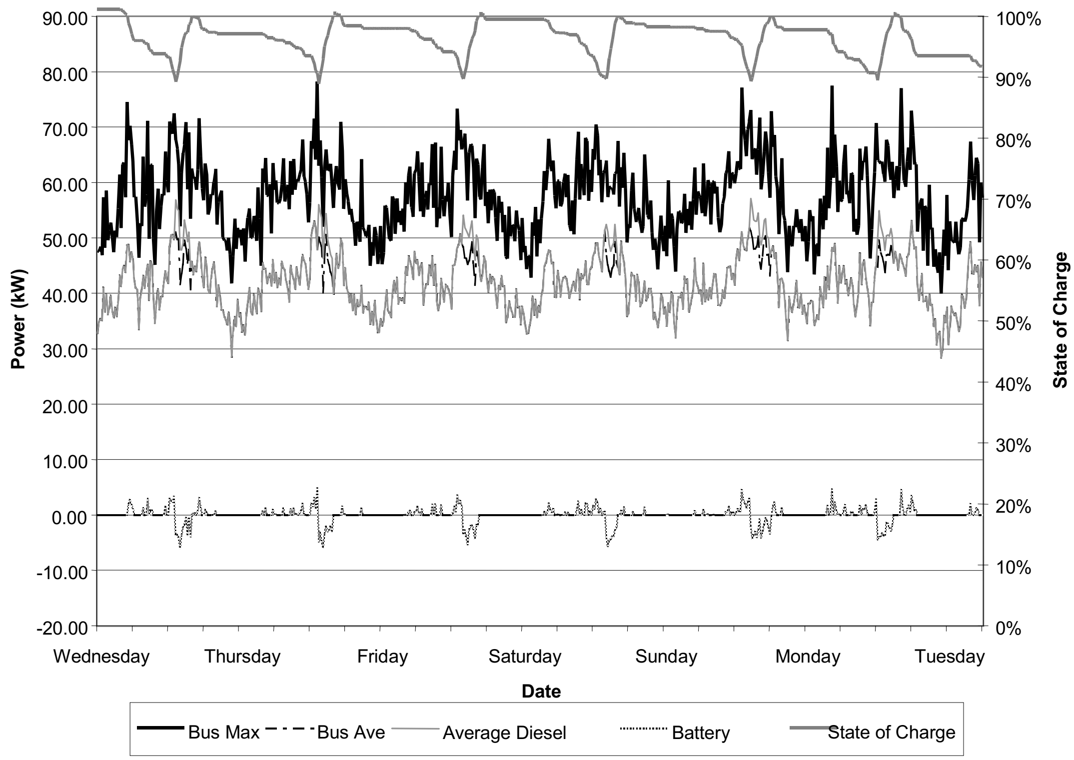


Figure 2-10. Chistochina Power Smoothing Fall and Winter, 45-kW Diesel.

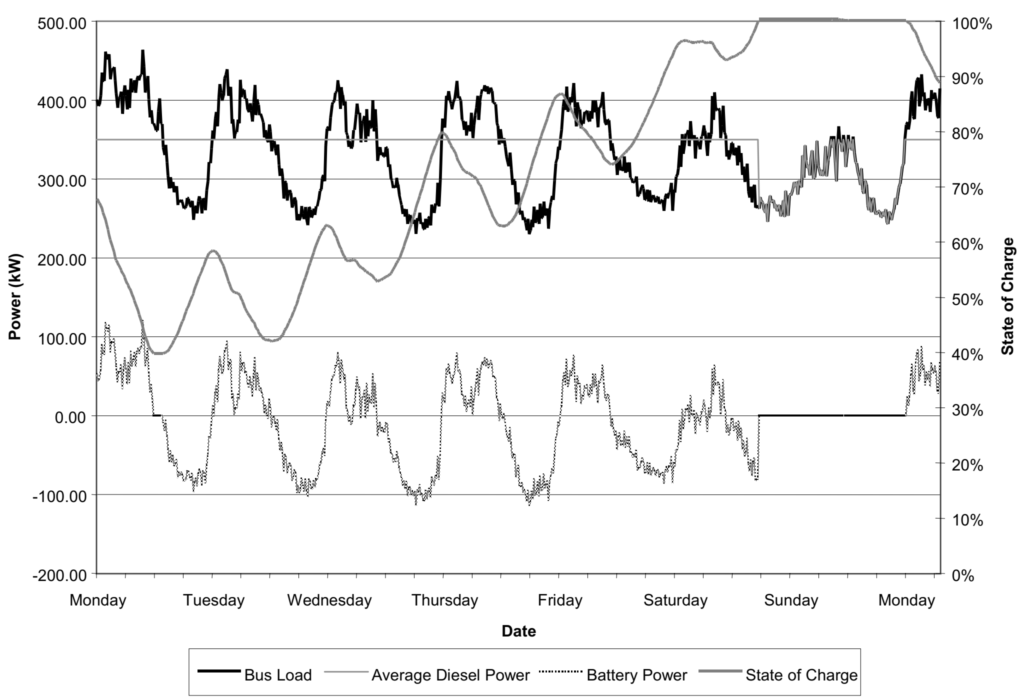


Figure 2-11. System Performance for One Week in Selawik – Fall and Winter.

Table 2-11. Summary of Results from Three Alaska Village Analyses

	Chistochina - A	Chistochina – B	Selawik
System Specifications	Genset: 60 kW	Genset: 45 kW	Genset: 350 kW
	Battery: 72 kWh	Battery: 72 kWh	Battery: 2.9 MWh
	BESS Cost: $60K	BESS Cost: $60K	BESS Cost: $1.2M.
Fuel Savings	12%	12%	6%
Simple payback period	7 yrs	7 yrs	50 yrs

transient peaks, Chistochina System B using a BESS for leveling the diesel loading, and Selawik, also using the BESS to level the diesel loading):

Note that the simple payback calculation for all three systems assumes a fuel price of $1.60/gal. For both Chistochina systems, the simple payback period is the same. This results from the equal fuel savings of both systems, as discussed previously.

Figure 2-12 shows actual power costs attributable to fuel ($/gal divided by kWh/gal) versus the fuel price for villages with less than 500-kW installed capacity (that is, very small villages). As expected, power costs generally increase as a function of fuel price, with the variation attributable to different generating efficiencies. The figure also shows a solid line indicating the leveled cost of energy from a battery/diesel hybrid (representing the cost of the ESS plus cost of fuel, not including diesel capital cost, maintenance, or overhead) from the Chistochina example. Villages plotted above this line should be able to economically use BESS at current battery and PCS prices. The dotted line shows leveled energy costs assuming the 72-kWh BESS costs $45K. This cost corresponds to the low-end projections for battery and PCS costs as found in the reports titled *Renewable Generation & Storage Project Industry & Laboratory Recommendations* and *Summary of State-of-the-Art Power Conversion Systems* for Energy Storage Applications. Achieving these cost goals will increase the potential Alaskan market from six to nine villages. The broken line shows the cost for BESS necessary to capture 50% of the small village market (about 24 villages), about $10K for the system considered (that is, a cost of 1/6th of the current $60K price).

Small villages have several characteristics that enhance the value of BESS, and maximize their ability to reduce fuel consumption. First, they use the smallest, most inefficient diesel gensets. Allowing these engines to run at their most efficient loading saves enough fuel to more than compensate for the inefficiencies introduced by the ESS. Additionally, smaller villages do not have a sufficient customer base to level out load spikes from individual customers. In a larger village with even as much as one hundred customers, the spikes caused by refrigerators cycling, lights turning on and off, and other uses of electricity tend to balance out and produce a relatively constant load (on a small-time scale, less than an hour). In a smaller village, diesel gensets must be sized substantially larger than even the "average peak" load, so that they can adequately cover the many transient peaks. This means that they spend more time running at lower efficiencies than units in larger villages. The analyses conducted for this study indicate that shaving these peaks and leveling the overall load of a small village can both be effective uses of BES. Such a system can save the villages approximately 12% in monthly fuel consumption for months that the system is operational (as many as nine months per year). Finally, smaller villages generally pay the largest premium for fuel because fuel cannot be purchased and transported at the bulk scale used by larger villages. This problem is compounded in more remote villages further from regional transportation hubs. High fuel costs coupled with high fuel savings serve to greatly improve the economics of BESS.

Based on computer modeling conducted for this study, BESS can provide an economical way to reduce fuel consumption in remote villages. The economics of such systems depend on several factors, including village size, fuel costs, and operating efficiency of existing equipment. Field studies of systems operating under actual conditions will help confirm the results of this model, as well as provide valuable experience in developing and operating these systems. Field studies will also allow for the evaluation of other potential system benefits, such as improved power quality and reduced maintenance costs. As systems improve in both cost and performance, they may become more economical in larger size villages. Ultimately, these systems could be an important part of reducing power costs in remote Alaskan villages.

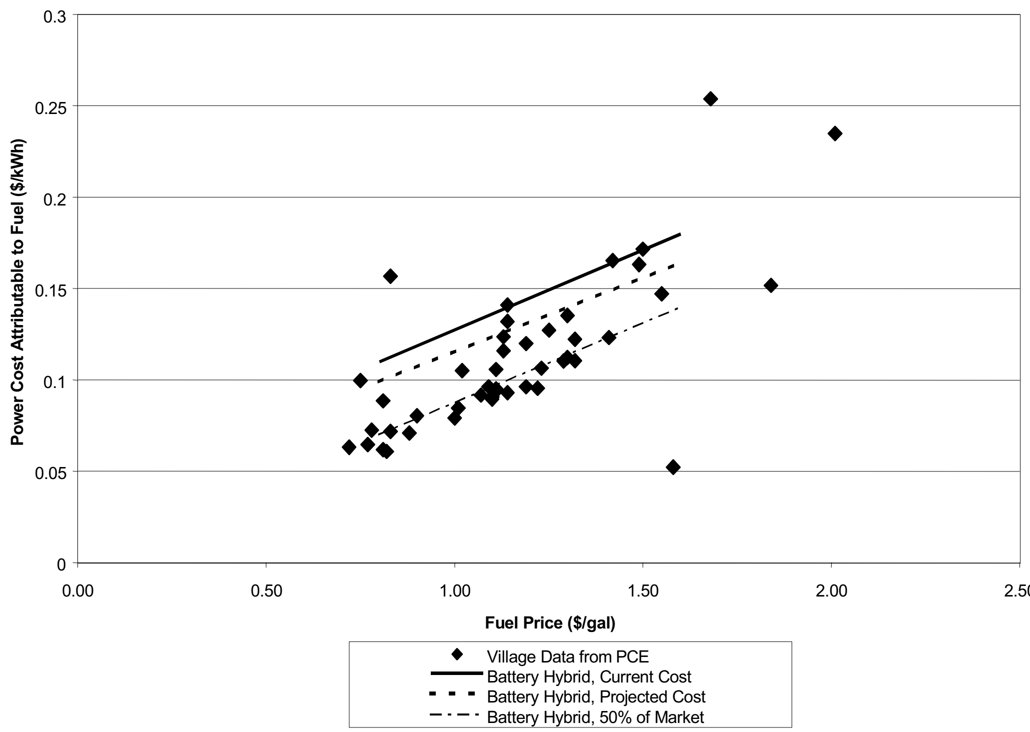


Figure 2-12. Fuel Price vs. Power Cost.

Renewable Generation and Storage and Related Projects

The RGS Project is an initiative that began in FY97. This project is envisioned as encompassing the investigation of modular, integrated RGS systems capable of control by utilities and other electricity suppliers. The RGS Project includes wind and PV generation options.

An integrated RGS system will provide a new option for the utilization of renewable generation. At present, renewable systems have typically been site-integrated; that is, components have been specified and purchased by a designer or an architect and engineering firm and then assembled at the final site. System integration using this approach may not always result in the lowest cost or most reliable system. In the case of several recent utility battery demonstrations, site integration caused significant start-up problems because of control interface mismatches, low-battery SOC resulting from prolonged storage without a charge, and power electronics failures. There are several examples of renewable systems that have been site-integrated that have had similar experiences.*

In addition, utilities have traditionally not given a high-capacity credit to renewable systems. This is because of the intermittent nature of most renewable generation and the inherent inability to dispatch such energy by the utility. An integrated, modular renewable system with storage can address many of these issues and thereby greatly increase the environmental and economic benefits of renewable technologies. An RGS system may be a cost-effective way to increase the stability of power from intermittent and fluctuating renewable resources and provide energy upon demand when the utility needs it the most, regardless of the availability of the renewable resource at that time.

Projects related to the RGS initiative include furthering cooperative relationships with renewable (PV and wind) programs at SNL and NREL. These programs utilize batteries in many of their laboratory and field experiments and have expressed interest in having technical contact with the ESS Program. These interactions are leading to increased collaboration on renew-

* Renewable Generation & Storage Project Industry & Laboratory Recommendations.

able technologies and storage among the national laboratories and will reduce duplication of effort and result in improved RGS systems.

Status

In FY98 the ESS Program issued a request for proposal (RFP) for the first phase in this project. Contracts were awarded to three companies to conduct three-month studies that focused on integrating ESSs with renewable energy generation. These studies were completed in FY98 and the results are summarized in SNL's ESS Program report SAND98-0883 for FY98.

In FY99, the final reports for each of the three contracts were published:

- AeroVironment, Inc.—SAND99-0936, *Solar-powered Systems for Environmental Remediation*
- Solarex—SAND99-1477, *Investigation of Synergy Between Electrochemical Capacitors, Flywheels, and Batteries in Hybrid Energy Storage for PV Systems*
- Ascension Technology, Inc.—SAND99-0935, *System and Battery Charge Control for PV-powered AC Lighting Systems*

The ESS Program determined that the results for Phase I were satisfactory enough to justify moving to Phase II of the project. Consequently, a second RFP was issued soliciting bids for follow-on work. Three proposals were received and evaluated by ESS Program staff and staff from the Photovoltaics Program at SNL. One contract for Phase II work was awarded to Ascension Technology, Inc., now a division of Applied Power Corporation (APC). Ascension Technology's final report for the Phase II work was submitted at the end of FY99 and will be published in FY2000. The results of Ascension's Phase II work, as documented in the final report, are summarized below.

Ascension Technology began this project by exploring the options currently available for stand-alone AC lighting systems. As required by the Phase I RFP, they identified a "technology gap" where existing technology did not meet consumer needs. In the case of AC lighting systems, Ascension determined that no intermediate-sized (35 to 100 W) lighting systems were currently available, despite consumer interest in the product.

To meet this need for intermediate-sized systems, the Ascension team reviewed currently available AC lamp technology and developed battery and load-charging specifications for an intermediate-sized system; they then developed a prototype design for a complete, stand-alone AC lighting system, including the power electronics.

PV modules, batteries, AC lamps, AC ballasts, fixtures, and luminaires are all mature mass-market technologies. The missing element in implementing a complete intermediate-sized PV-powered AC lighting system is an integrated controller to tie all of these components together to form a reliable, high-quality system. The work completed during Phase I resulted in a patent application being filed for such a controller. The purpose of the application is to "prevent early failure of either the lighting load or the battery" in a PV-powered AC lighting system. Work during Phase II of the project focused on further developing the prototype controller to a point where it would be suitable for field and laboratory testing.

The prototype controller described in the patent application has two main features that address the reliability of industrial-grade AC lighting systems. First, the application says, "the system reduces injection of DC current into the load and, as a result, extends the operation life of the load, particularly if the load is an AC lighting lamp or system." Second, "the system operates the load in an optimal manner so that battery storage is maintained near full charge, yet the lighting load operates for a maximum number of hours per night.

Smart, adaptive algorithms in the controller and inverter determine how long the light can operate each night. Initially the light operates on preset hours of operation entered by the user, but as the system learns about battery capacity and lighting load, it begins to automatically control how long the light is on so that the battery SOC is maintained high rather than low. The system learns the characteristics of the battery by measuring voltage, charge and discharge current, and temperature over a period of weeks.

One of the advantages of this type of system control is that the system design-day no longer has to be the worst day of the year. PV lights that are located in a recreational area that is used only in the summer can be sized for operation in the summer. As sunlight availability begins to decrease through the winter months, the system will automatically operate the light a reduced number of hours. Also, as battery capacity begins to decrease, so too will operating hours of the light. If an installer makes a mistake and undersizes the PV array, the controller will automatically adjust how long the lights stay on so that battery health is maintained. A further benefit of this system is that it should be able to prevent premature battery failures caused by prolonged operation at low SOC because not enough PV power is available to maintain battery health.

Work in Phase II included improving this system controller, designing and building a prototype AC lighting system, identifying potential demonstration sites, and developing a test plan that would adequately evaluate system parameters.

Prototype AC Lighting System Components

A prototype system, which uses an improved version of the charge controller described in the patent application, was delivered to SNL in late August for evaluation. The major components of this prototype system are batteries, PV modules, an enclosure for the batteries and power electronics, a "top of pole" mount for the PV array, the system controller, and the light fixture. Specifications for each of these components are provided in Table 2-12. Note that the complete system includes the lighting pole and mounting arm for the light fixture. These items were provided by SNL.

The prototype controller was delivered with On/Off series charge control, but this may be changed to high frequency pulse width modulation (PWM) charge control later with firmware upgrades. The prototype was delivered with very basic control firmware (Table 2-13). The first step for testing the prototype will be to validate the charging and inverter power electronics. Once the hardware is deemed stable, the more sophisticated firmware will be provided for the unit. Firmware and hardware upgrades may be provided periodically to SNL as product development continues.

An approximate scale sketch of the system design is shown in Figure 2-13. An electrical schematic diagram of the system is shown in Figure 2-14. Specifications for the lighting system, the data collection system, and general specifications for the overall prototype design are presented in Table 2-14.

In addition to the lighting specifications, the system must also use Underwriter's Laboratory (UL) listed components and be able to be installed in accordance with the National Electric Code. Those requirements are too voluminous to repeat here, but are applied to things such as DC/AC isolation, separation of circuits, grounding of the system, proper installation instructions, etc. The reader is directed to UL 1741 and NEC Article 690 for further details.

The prototype system was sized for operation in Albuquerque, New Mexico. The system is sized for year-round operation, all night long. During testing of the system, PV can be reduced by changing the tilt angle of the array. See the Test Plan below.

In addition to the system specifications, Table 2-15 lists specific items that apply to the system.

Candidate Demonstration Sites

Each demonstration site should be a location where the cost to install PV-powered light is lower than using utility power or where high service reliability is needed, such as perimeter security lighting. Most applications will probably be in somewhat remote locations. Performance of these lighting systems will depend upon varying levels of sunlight from region to region, as well as varying weather and temperature. Consequently, one large demonstration system in one location would not be representative of how the product is expected to be used. Therefore it was proposed to co-locate systems with Ascension's customers in many regions of the country.

Table 2-16 shows a proposed list of customers who would be willing to provide demonstration sites. Each customer will have one system that is instrumented with a remotely operated DAS. The purpose of the DAS is to monitor battery parameters: voltage, charge/ discharge current, and temperature as well as plane of array (POA) irradiance.

Installation plans will vary from site to site. APC will provide technical support to customers to ensure successful installations and plans to provide sufficient documentation so that an average contractor can successfully install the systems. If PV systems experts have to be sent into the field to install single lights, the systems will not be cost effective. For this application to be successful, it must be installable by the average contractor.

Test Plan

Should a full demonstration be funded, systems with data collection instrumentation would be installed first. As systems become operational, data collection will be done remotely from APC's Waltham, Massachusetts, offices. Each instrumented system will monitor the following parameters:

- Battery voltage
- Battery current, charge and discharge
- Battery temperature
- POA irradiance

Table 2-12. Prototype AC Lighting System Specifications

Battery Specifications	
Model	SES B2600B (12 V)
Qty/system	4
Nameplate capacity	95-Ah/battery
Type	Gel, non-spillable
PV Specifications	
Manufacturer	Siemens
Model	SR100
Qty/system	2
Rating	100-W/module
	12 V
	5.6 A
Connection	Series connected for 24-V operation
Dimensions	59 × 23.4 × 2.2 (in) each
Weight	24 lbs each
Enclosure Specifications	
Manufacturer	SES
General	Locking, vented, rainproof.
	Used in UL Listed MAPPS products.
	National Equipment Manufacturer's Association (NEMA) 3R equivalent

Table 2-12. Prototype AC Lighting System Specifications (continued)

Enclosure Specifications (Continued)	
Dimensions	17 × 20 × 38 (in)
Mount Method	Brackets included for round- or square-pole mount, 2 to 5 (in) diameter
Weight	380 lbs. (approximately) with 4 batteries and controls
System Protection	10-A PV breaker
	30-A Battery breaker
	2.5-A AC light breaker
Wiring Method	Bulkhead mounted, weatherproof-quick electrical disconnects for easy connection of PV and AC Load. No internal wiring required at time of installation other than hook-up of batteries.
Top of Pole PV Mount Specifications	
Distributor	SES
Part No.	T3573
Pole Mount Diameter	Schedule 40, 4" Pipe (4.5" actual) diameter
Array Tilt Angle Adjustment	15 to 80º
Azimuth Angle Adjust	0 to 360°

Table 2-13. Prototype System Controller Specifications

Manufacturer	Applied Power Corporation
Model	LC-100 (prototype)
PV Input	60 V max volt open circuit (Voc)
	24 A max charge rate
	40 V typical Voc
Charger Type	On/off series controller
Charge Set Points	32.0 V over-voltage shut-down
	28.2 V disconnect voltage (Vr)
	27.4 V reconnect voltage (Vrr)
	26.0 V low voltage discon-nect and reconnect (LVDR)
	23.4 V low voltage discon-nect (LVD)
Reverse Polarity Protection	Yes
Day/Night detection	PV array voltage
AC Output	125/230 V (switch select-able)
	60/50 Hz (dip switch select)
	150-VA design rating (Tested to 60 VA so far)
Inverter efficiency	85% (will be improved as design matures)
	90% design target
AC/DC Isolation	2-kV min transformer isola-tion
DC blocking	Transformer
Power On Soft Start	Yes
No Load shutdown	To be determined

Table 2-13. Prototype System Controller Specifications (continued)

User Inputs	16 position select switch (for operating mode)
	4 pos. dip switch
	50/60 Hz select
	Flooded/Gel
	TBD (to be determined)
	Test button for 5 minutes of light operation
User Display	PV Charging indicator light emitting diode (LED)
	Power ON LED/misc test code display
	AC Light ON indicator LED
Battery connection	24V (nominal)
	20- to 35-V operation
DC System Grounding	Positive ground
Light Fixture Specifications	
Manufacturer	General Electric
Model	M-250/A2
Lamp Rating	50-W HPS
AC Load	60-W typical
Power Factor Cor-rection	Yes
Light Sensor	Not required, but may be used.
Style	Cobra-head style luminaire
Mount Method	Horizontal mount on 1.25”-2.00” pipe.
Dimensions	11.5 × 13.25 × 27.5 (in)
Weight	25 lbs

Table 2-14. Prototype System Specifications

Lighting System Specifications	
Lighting load	50 W high-pressure sodium (HPS) with power factor corrected ballast.
Light height	20 ft
Pole height	25 ft
Pole mount	Standard concrete ground mount with breakaways
Array mount	Top of pole mount with adjustable tilt angle
Array tilt angle	Varies depending upon location, whether lighting will be provided for year-round use or seasonal use, and data from NREL Solar Radiation Handbook.
Hours of light operation	Varies depending upon application. In some cases all night operation is desired; in some cases split evening and morning operation are desired, etc. The system must be capable of being sized for all night operation.
PV Array Sizing	Depends upon the solar resource and lighting load requirements. Typical array sizes would be 200 or 300 W at 24 V.
DC system voltage	24 V
AC system voltage	120 V 60 Hz
Maintenance interval	Yearly maintenance, system checkout, cleaning.
	Battery replacement, typically at 4 years, but with the new controller this is TBD.
Wind design load	100 mph

Table 2-14. Prototype System Specifications (continued)

Data Collection System Specification	
Data logger type	Campbell Scientific, CR 900
Communication	Cellular modem
Remote data capability	Yes, dial up to download historical data as well as current operational data.
Measured parameters	Plane of array (POA) Insolation
	Battery temperature
	Battery voltage
	Charge/discharge current
Data logging interval	10 minutes, average of all measurements during previous 10 minute interval. Date and time stamping included.
Maintenance interval	Only when data system indicates maintenance is required.
Packaging	The data logging equipment will be included in the electronics compartment of the battery box along with the LC100 system controller.
Power supply	The data logger will operate off of the same 24-V battery bank as the lighting system. A separate battery disconnect will be provided so that the controller can be powered off while maintaining power to the data system.

Table 2-15. Prototype Design Specifications

Array tilt angle	50°
Design month	December
Design sun-hours	5.8
PV array rating	200 W
Estimated battery efficiency	80%
Inverter efficiency	90% (target)
AC load	60 W
Hours operation/night	13.92 hours/night
DC load amps	2.67 A
Discharge rate	C/71
Days autonomy	5.1
Battery capacity	190 Ah @ 24 V

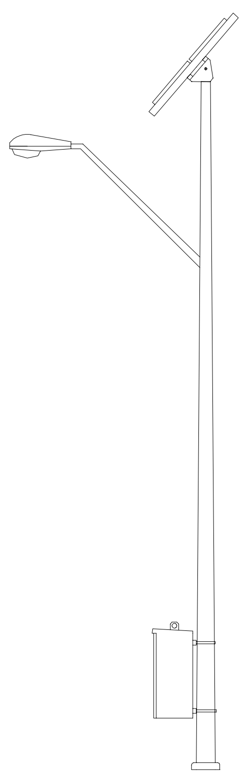


Figure 2-13. System Design (approximately to scale).

Data will be monitored continuously, and average data for each period will be stored to memory every 10 minutes by the on-site DAS. During the first full year of operation, data will be collected from each system weekly.

A mathematical system performance model will be developed for checking the collected data. The collected data will be compared against this model to determine if the system is performing within limits. The questions that should be answered by the collected data include:

- Are the controllers operating properly to maintain batteries near high SOC most of the time?
- Is there room for improvement in system performance?
- Could the systems operate the load longer and still maintain battery health?
- Are the systems operating the load too much and drawing down the battery too much?
- Are there any hardware failures? If so, of what nature are they?

Because the charger is microprocessor controlled and has provision for serial I/O, providing an interface between the DAS and the system controller may be a consideration. The purpose of this type of interface would be to allow remote modification of the controller algorithm and to collect data only known to the controller, such as estimated SOC.

After one year of testing, a report on system performance and lessons learned will be prepared. It is important to test for a full year; otherwise some seasonal operating effects may be omitted.

Evaluation of the prototype system using the test plan described above continues at SNL. The next step in commercializing this product would be toward laboratory testing and further design iterations of the system controller. The test plan and milestones for such testing are presented in the final report for this contract, which will be published in FY2000.

System Evaluation

Mobile Power-Quality System

The goal of the Mobile Power-Quality System Project is to further the development of prototype battery systems built with commercially available and advanced components and to evaluate these systems in typical utility operating environments. The project covers the design, fabrication, siting, installation, testing, and reporting on these systems. The systems are designed to be moved to a new location (on the same or

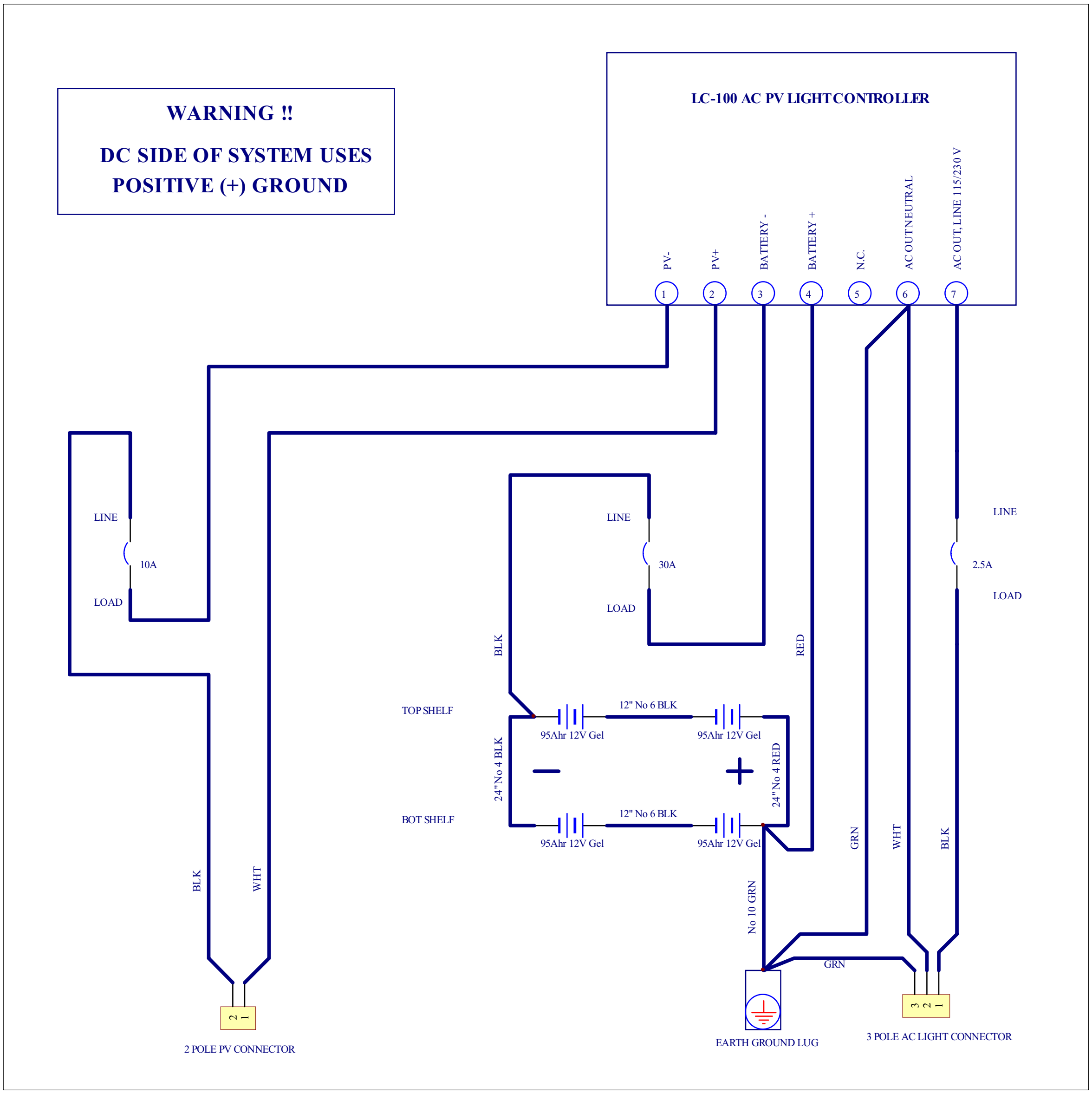


Figure 2-14. System Electrical Schematic.

on a different utility grid), installed, and tested. They are being developed for use by one or more utilities over several years to obtain field data at more than one site to prove reliability, functionality, and cost-effectiveness.

Status

On September 5, 1998, the Mobile PQ2000 system was installed at the service entry of a printing plant in Richmond, Virginia. Two hours after the system was installed, a power failure for the plant was averted as the system sensed a sag and activated to support the plant until power was restored. Three days later, a fault in the feeder lines between the Mobile PQ2000 and the plant resulted in a fire in the conduit, which led to a shutdown of the entire plant. Although the unit was not responsible for the problem and in no way contributed to the fault, plant management requested that the system not be re-installed when the repairs were completed. Consequently, the Mobile PQ2000 was placed in temporary storage at the Virginia Power Iron Bridge facility where it remained at the end of the quarter while Virginia Power sought out a new customer.

Following the reinstallation and start-up of the Mobile PQ2000 at the Iron Bridge facility, no further system testing or operations were performed other than maintenance of battery charge to ensure that the batteries remain at top of charge. Efforts continued

Table 2-16. Proposed Demonstration Sites

Customer	Location	Qty of Lighting Systems Standard/with DAS
Black Hills Power & Light	South Dakota	3/1
National Park Service	Northwest	3/1
U.S. Forest Service	Northwest	3/1
Bureau of Land Management	West Virginia	3/1
General Services Administration	Washington	3/1
Northern States Power	Minnesota	3/1
Austin Energy (formerly City of Austin Electric)	Texas	3/1
Northeast Utilities	Connecticut	3/1
Wisconsin Public Service	Wisconsin	3/1
Tucson Electric	Arizona	3/1
Arizona Public Service	Arizona	3/1
NREL, Outdoor Test Facility	Colorado	1/1
SNL	New Mexico	3/1
	Total	37/13

throughout the second quarter to find a new owner for the system. The Mobile PQ2000 remained connected to the utility at the Virginia Power Iron Bridge Facility until a new customer location was found.

In early May, a lease agreement for the system was reached between Virginia Power and S&C Electric Company. On May 13, 1999, the Mobile PQ2000 was removed from the Iron Bridge facility in Richmond, Virginia, and began its journey to the S&C Electric Company plant in Chicago, Illinois. The over-the-road PQ2000 configuration is shown in Figure 2-15. The unit arrived at S&C on Friday, May 14, at 8:30 p.m. S&C installed the unit to protect their polymer product fabrication plant as shown in Figure 2-16. On Saturday, staff from Omnion's production group were on site to perform the pre-energization checks. S&C installed the 480-V buss taps to feed the Mobile PQ2000 and energized the buss on Sunday. Omnion personnel completed the on-site start-up testing with a 250-kW load bank on Monday. On Tuesday, the system was fully operational and was placed on line. Several hours later, the unit responded and protected the plant from a power interruption that would have resulted in shutdown of critical plant equipment.

The Mobile PQ2000 is scheduled to remain at S&C Electric through the first quarter of FY2000. Monitoring and analysis of system operation will be conducted by S&C and reported to SNL. Details of the performance and system analysis will be available in future SNL reports.

VRLA Battery Test at Vernon

A cost-shared development effort was initiated in FY91 with GNB for the improvement of VRLA battery designs to meet utility application requirements in the mid- to late 1990s. Existing VRLA batteries were designed to meet the needs of automotive, telecommunication, and industrial applications, not utility applications, which have different operating conditions. The GNB effort developed and put into production improved VRLA batteries designed to meet these utility needs.

The final deliverable from the development program consisted of a large battery (250 kW/500 kWh) whose operation was to be evaluated in a field test. In the beginning of FY96, a contract was awarded to GNB to perform this testing over a four-year period. Costs for the test are being shared by GNB at 50%. The deliverable battery has been incorporated into a 3.5-MW/3.5-MWh battery system that has been installed by GNB at its lead-recycling center in Vernon, California. To match the rest of the battery system planned for Vernon, and because of its established production capability, the battery design chosen as the deliverable was the ABSOLYTE IIP. The primary application for the battery system at Vernon is to provide emergency backup power to critical loads at the facility dealing with environmental (air emission) controls. It is also

Figure 2-15. Mobile PQ2000 in Transit.

Figure 2-16. The Mobile PQ2000 Installed and Operating at S&C Electric Company.

being used in a peak-shaving mode for demand reduction that will lower electricity demand charges for the facility and take advantage of lower off-peak energy costs.

The battery system has been in operation since the first quarter of FY96. Tests of the peak-shaving mode began in July 1997 and have continued in FY98 and FY99. A primary objective of these tests was to find the optimum trigger power level for the battery system to supply the plant demand during peak shaving. The desired nominal DOD for the battery is 30 to 40%, with the remainder of the capacity being reserved for plant support during utility power outages. Ground-fault problems resurfaced during the first part of FY98, causing the load peak-shaving function to be unavailable for part of the time. Extremely wet weather conditions during the fall and early winter were believed to be a significant contributor to this situation. Computer malfunctions in the data storage system also occurred frequently during this same time. During the spring, both of these causes for BESS outages abated enough to resume load peak shaving, although ground-fault alarms were still commonly found. Replacement of a number of suspect leaking cells seemed to temporarily reduce the occurrence of ground faults. In May 1998, aggressive peak shaving was resumed, and the trigger level remained set at 3100 kW for the last five months of the fiscal year. In September 1998, the battery SOC at the end of the peak-shaving period was approaching the desired 60 to 70% range. During FY99, the goal of this testing was to operate in the peak-shaving mode consistently enough to observe seasonal variations in the optimum threshold setting, if any.

Status

Peak shaving operations continued smoothly into the month of October 1998, with a reduced trigger level setting of 3050 kW. On October 15, PCP#2 (inverter) tripped for unknown reasons at approximately 3:30 p.m. This was discovered several hours later and remedied via a basic system reset. As a result, peak shaving benefits were nullified for the month, so it was decided to disengage peak shaving for the balance of the month. The BESS, however, continued to function in its primary role of UPS support.

With daily peak shaving now inactive, GNB made efforts to address ground fault sensitivity concerns. On October 22, the ground fault resistors had like resistors added in parallel connections inside the ground fault cabinet, thus halving the resistance and doubling the current required to trigger a ground fault alarm. The intent of this modification was to allow higher ground fault current, which would expedite the evaporation of any electrolytic pathways generated by (a) cell leaks or (b) excess moisture in the BESS facility. Cell surface heating was computed to be insignificant, so system integrity was not threatened by this modification.

By the day after the modification, ground fault alarms were no longer continuous; they tended to cycle on and off as electrolytic pathways were now evaporating within three hours of triggering an alarm condition. This modification appeared promising and may be a positive step in achieving the virtually “hands-off” system that the BESS was designed to be.

During the months of November and December 1998, engineers from General Electric (GE) performed a comprehensive preventive maintenance inspection of all non-battery components. This required the BESS to be offline several times throughout these months, so peak shaving remained disengaged until the inspection was complete. Overall, several items were discovered and corrected on the BESS as a result of the GE maintenance inspection.

Peak-shaving operations resumed during the second quarter. The peak-shaving trigger level was maintained at 3050 kW in January. In February and March, the trigger level was further lowered to 3000 kW.

On February 27, 1999, plant-take-over and performance tests were conducted on the BESS, which proved to be a great success and a milestone in demonstrating the system’s reliability. These tests were intended to achieve the following objectives:

1. Verify operation of all of the BESS components that were inspected during GE’s preventive maintenance inspection in the previous quarter.

2. Examine the smelter plant’s primary incoming breaker components (which may be examined only when the plant is taken off utility power).

3. Demonstrate that the BESS will recognize a loss of utility power and compensate appropriately as designed.

4. Demonstrate that the BESS resynchronizes and reroutes utility power smoothly and flawlessly when terminating UPS support. (Both modes of power restoration, Manual and Automatic Restore, were tested following outage conditions.)

5. Observe and document remaining concerns about long-term system performance.

6. Qualify as an acceptance test the overall operation, performance, and integrity of the BESS.

Without question, the BESS met all requirements outlined in the test sequence. Deficiencies identified in previous months had been resolved, and the BESS demonstrated its ability to perform in both the peak-shaving and the UPS modes of operation.

BESS operation in the second quarter successfully demonstrated abilities as a primary backup system. In addition, there was further progress toward achieving optimal battery utilization during winter peak-shaving periods. Aggressive peak shaving is a way to minimize costs during on-peak hours of utility demand. It is believed that during winter on-peak utility hours, an optimum trigger level will be achieved at approximately 2925 to 2975 kW. The first and second quarter data are presented in Appendix A.

Peak shaving continued smoothly throughout the third quarter. Tables and charts showing key operating characteristics for the battery as well as plant demand are presented in Appendix A. To complete the preceding winter season, the BESS' peak-shaving trigger level was lowered to 2975 kW for the month of April. Average weekday DOD was only 79.9%, so optimum winter peak-shaving settings were now surmised to be near 2925 ± 25 kW. For the months of May and June, the peak-shaving trigger level was raised slightly to 3100 kW to compensate for the longer hours during the utility's summer season on-peak demand window (12:00 p.m. to 8:00 p.m. weekdays).

As of June 1, 1999, the choice of BESS peak-shaving settings was handed over to the local engineering staff at the Vernon smelter facility, to which the BESS provides its support. For May and June, the average weekday DOD was only 87.1% at the 3100-kW trigger level selected, so a more aggressive setting was adopted in the months to follow as the local engineering staff gained more understanding of their facility's on-peak demand characteristics.

Peak shaving operations continued relatively smoothly throughout the fourth quarter (July through September 1999). Tables and charts showing key operating characteristics for the battery and plant demand are shown in Tables 2-17 through 2-19 and Figure 2-17. For the months of July and August, the peak shaving trigger setting was maintained at 3100 kW as the on-site engineering staff became accustomed to the BESS' overall operating characteristics while determining optimal peak shaving parameters. BESS peak shaving operation was only moderately aggressive for these two months, with the average weekday SOC dropping to 77.5 and 78.0%, respectively, for July and August.

In September, the peak shaving trigger setting was lowered to 3025 kW. During summer on-peak hours, this setting was anticipated to be the initial optimal level of peak shaving at which maximum cost savings can be attained while still maintaining the BESS within the proper SOC window to continue peak shaving on any given weekday of the month. On Sunday, September 26, inverter No. 2 experienced an instant fault due to two loose relay connections within the inverter unit itself. GE's service group was notified the following morning (Monday), however scheduling did not permit them to repair the problem until Tuesday morning, September 28. Because of this, the BESS was unable to perform its peak shaving duties on Monday, thereby allowing the Vernon utility to realize a larger kilowatt demand from the smelter plant. It was observed that Monday's on-peak period generated a kilowatt demand of approximately 3480 kW, so the peak shaving trigger level was adjusted to 3500 kW so as to offset any more costs (via having a demand greater than 3500 kW) for the balance of the month.

The fourth quarter BESS operation was largely routine with the exception of the last three days of the quarter. Peak shaving will begin the next quarter at an aggressive level of 3025 kW, with anticipation of going lower as the winter season approaches. The BESS has been virtually hands-off, performing both (a) its primary purpose of UPS support, and (b) providing aggressive peak shaving benefits. No alarm conditions were encountered, and attention to the BESS was minimal with the exception of periodic data acquisition.

Further, in August the Vernon BESS interface computer was replaced in order to ensure Y2K compliance. The interface computer is what permits GNB engineers to manipulate the BESS' peak shaving settings, as well as to observe its performance, alarm status, trending, event histories, overall one-line status, and data acquisition, etc. A new Windows NT-based system was installed, with upgraded software and hardware components. The new interface computer was tested for all critical Y2K dates, and passed all tests successfully.

Field Test Data Management Project

In FY99, SNL initiated a project to develop a comprehensive database of current fielded battery energy storage systems for off-grid, stand-alone, and grid-tied

Table 2-17. July 1999 Data from Vernon BESS Operations

July 1999: 3050-kW Peak-Shaving Trigger Level

Date	Day of the Week		No. of Discharge Operations During Required Demand Period	Average kW During Required Demand Period	Largest Peak During Peak-Shaving Period	Difference Between Largest & Average kW Values (at left)	Lowest SOC During Peak-Shaving Period
07/01/99	R		586	3065	3481	416	90 %
07/02/99	F		544	3041	3435	394	87 %
07/03/99	Sa		249	2938	3445	507	92 %
07/04/99	Su		0	2821	3083	262	94 %
07/05/99	M		8	2920	3162	242	93 %
07/06/99	T		391	3032	3490	458	91 %
07/07/99	W		651	3085	3475	390	86 %
07/08/99	R		343	3030	3465	435	92 %
07/09/99	F		551	3066	3505	439	86 %
07/10/99	Sa	*No PS*	-	2891	3202	311	-
07/11/99	Su	*No PS*	-	2936	3405	469	-
07/12/99	M		639	3080	3488	408	77 %
07/13/99	T		725	3087	3490	403	74 %
07/14/99	W		722	3081	3502	421	89 %
07/15/99	R		632	3045	3487	442	88 %
07/16/99	F		807	3092	3516	424	73 %
07/17/99	Sa	*No PS*	1148	3130	3409	279	-
07/18/99	Su	*No PS*	616	3065	3315	250	-
07/19/99	M		805	3092	3483	391	71 %
07/20/99	T		826	3099	3587	488	63 %
07/21/99	W		1036	3103	3470	367	67 %
07/22/99	R		885	3101	3518	417	71 %
07/23/99	F		747	3099	3502	403	58 %
07/24/99	Sa	*No PS*	1950	3220	3470	250	-
07/25/99	Su	*No PS*	1385	3143	3627	484	-
07/26/99	M		747	3099	3503	404	79 %
07/27/99	T		777	3099	3506	407	75 %
07/28/99	W		693	3101	3573	472	53 %
07/29/99	R		731	3094	3482	388	88 %
07/30/99	F		859	3101	3513	412	55 %
07/31/99	Sa	*No PS*	2146	3199	3420	221	-

(Note: Data acquired from BESS has 10-sec sample rates on discharge and 3-min on recharge.)
PS = peak shaving

Largest of the month:			3627	
Average for entire month:	765	3063	3452	78.8 %
Average for weekdays only:	668	3073	3483	77.5 %

Table 2-18. August 1999 Data from Vernon BESS Operations

August 1999: 3000-kW Peak-Shaving Trigger Level

Date	Day of the Week		No. of Discharge Operations During Required Demand Period	Average kW During Required Demand Period	Largest Peak During Peak-Shaving Period	Difference Between Largest & Average kW Values (at left)	Lowest SOC During Peak-Shaving Period
08/01/99	Su	*No PS*	1333	3172	3480	308	-
08/02/99	M		568	3077	3542	465	81 %
08/03/99	T		479	3074	3638	564	83 %
08/04/99	W		564	3071	3525	454	90 %
08/05/99	R		672	3078	3478	400	60 %
08/06/99	F		541	3074	4097	1023	50 %
08/07/99	Sa		72	2975	3493	518	90 %
08/08/99	Su		636	3076	3420	344	87 %
08/09/99	M		728	3095	3602	507	69 %
08/10/99	T		605	3099	3452	353	73 %
08/11/99	W		865	3097	3511	414	69 %
08/12/99	R		717	3096	3543	447	73 %
08/13/99	F		594	3066	3515	449	89 %
08/14/99	Sa	*No PS*	1139	3141	3517	376	-
08/15/99	Su	*No PS*	1747	3213	3529	316	-
08/16/99	M		639	3067	3476	409	85 %
08/17/99	T		513	3001	3486	485	71 %
08/18/99	W		786	3099	3511	412	75 %
08/19/99	R		839	3101	3622	521	69 %
08/20/99	F		2160	3100	3480	380	82 %
08/21/99	Sa	*No PS*	1117	3131	3411	280	-
08/22/99	Su	*No PS*	752	3102	3439	337	-
08/23/99	M		616	3070	4617	1547	86 %
08/24/99	T		607	3094	4730	1636	78 %
08/25/99	W		508	3085	5079	1994	88 %
08/26/99	R		836	3096	4755	1659	74 %
08/27/99	F		740	3079	4521	1442	91 %
08/28/99	Sa	*No PS*	838	3140	3617	477	-
08/29/99	Su	*No PS*	1116	3106	3424	318	-
08/30/99	M		898	3096	4604	1508	89 %
08/31/99	T		854	3071	3584	513	90 %

(Note: Data acquired from BESS has 10-sec sample rates on discharge and 3-min on recharge.)
PS = peak shaving

Largest of the month:			5079		
Average for entire month:	809	3092	3764		78.8 %
Average for weekdays only:	742	3081	3880		78.0 %

Table 2-19. September 1999 Data from Vernon BESS Operations

September 1999: 3000-kW Peak-Shaving Trigger Level

Date	Day of the Week		No. of Discharge Operations During Required Demand Period	Average kW During Required Demand Period	Largest Peak During Peak-Shaving Period	Difference Between Largest & Average kW Values (at left)	Lowest SOC During Peak-Shaving Period
09/01/99	W		184	2816	3361	545	93 %
09/02/99	R		28	2612	3786	1174	93 %
09/03/99	F		370	2919	3721	802	88 %
09/04/99	Sa	*No PS*	1012	3015	3348	333	-
09/05/99	Su	*No PS*	1038	3051	3318	267	-
09/06/99	M	*No PS*	254	2998	3257	259	-
09/07/99	T		630	3020	3410	390	61 %
09/08/99	W		854	3024	3584	560	60 %
09/09/99	R		1193	3026	3442	416	76 %
09/10/99	F		832	3021	3380	359	61 %
09/11/99	Sa	*No PS*	2103	3165	3390	225	-
09/12/99	Su	*No PS*	2132	3236	3657	421	-
09/13/99	M		826	3022	3448	426	58 %
09/14/99	T		980	3027	3424	397	68 %
09/15/99	W		891	3025	3422	397	69 %
09/16/99	R		838	3025	3487	462	52 %
09/17/99	F		923	3025	3427	402	74 %
09/18/99	Sa	*No PS*	2107	3174	3342	168	-
09/19/99	Su	*No PS*	1811	3092	3465	373	-
09/20/99	M		1009	3013	3210	197	90 %
09/21/99	T		1042	3025	3125	100	92 %
09/22/99	W		1282	3028	3353	325	89 %
09/23/99	R		784	3026	3380	354	66 %
09/24/99	F		877	3026	3454	428	58 %
09/25/99	Sa		1391	3028	3336	308	91 %
09/26/99	Su		2160	3267	3637	370	-
09/27/99	M		2160	3385	4010	625	90 %
09/28/99	T		443	3399	3842	443	91 %
09/29/99	W		504	3433	3849	416	91 %
09/30/99	R		263	3318	3800	482	92 %

(Note: Data acquired from BESS has 10-sec sample rates on discharge and 3-min on recharge.)
PS = peak shaving

Largest of the month:			4010	
Average for entire month:	1031	3075	3489	77.4 %
Average for weekdays only:	780	3055	3508	76.8 %

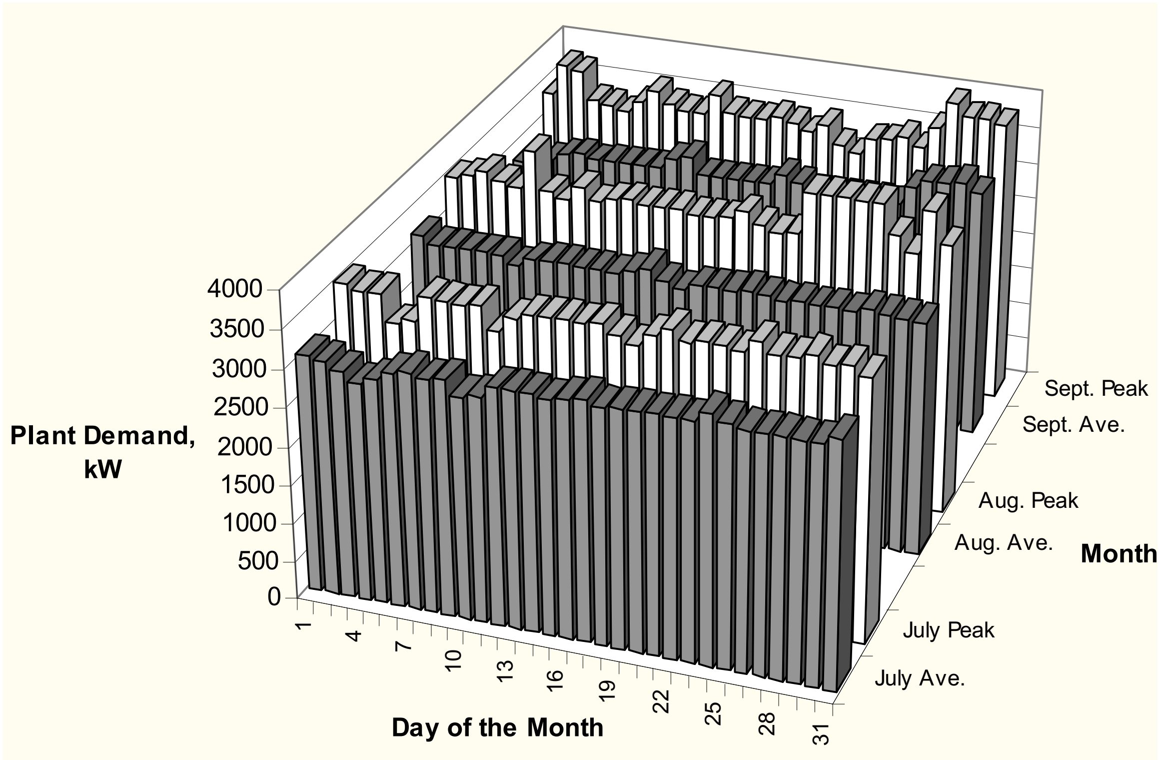


Figure 2-17. Average and Peak Plant Demand at Vernon for the Months of July, August, and September 1999.

systems. The purpose of the database is to provide information on the operation and management of these systems in order to learn how to design future systems to avoid problems identified from the evaluation of fielded systems. The database is intended to provide practical field performance data for potential customers.

Four contractors were selected for the initial phase of the project, two for off-grid analysis, and two for on-grid analysis. The first task was to identify a site that would provide historical data for an energy storage system in operation that met the criteria for analytical tasks called out in the contract. Primary tasks included:

- Acquiring data, in comma-separated variable (CSV) format that was generated by the existing data acquisition systems (DASs);
- Evaluating data quality and making reliability decisions as appropriate;
- Developing a Microsoft Access database for the data; and
- Designing analytical tools to perform initial analyses of the system to determine the performance of the system.

Additional tasks were to determine the adequacy of the DAS used for the fielded systems, determine the adequacy of the battery management strategy applied to the fielded system, and to make recommendations for ways to increase the reliability of DASs. Because of the diversity of the fielded systems, contracts were issued for both off-grid and grid-tied applications with the intent to develop a common database for all storage applications to assist in future data review and analysis. Although the four applications selected for analysis are very different from each other, it is anticipated that all performance information will ultimately reside in a single database.

To develop the initial database structure, a data kernel was defined that was anticipated to apply to all battery applications. The kernel consisted of the following time-referenced parameters:

- Ah lifetime accumulation,
- Wh (AC and DC) lifetime accumulation,
- State of charge,
- System DC voltage,
- Overcharge (%),
- System power,
- DC current, and
- Battery temperature.

The kernel also included the duty cycle count, and failures and/or problems, which would not be time referenced. The kernel would be identical for all systems evaluated. Because of the diversity of the systems, it was anticipated that unique features for each system would also need to be included in the database, they would connect only to the specific system to which they related. The four contractors were directed to focus on the design of a database that fully supported their individual system with an eye toward the integration of the three other systems into the database structure and analytical tool application.

It is anticipated a follow-on effort will be required in FY2000 to wrap up the work started in FY99. The following sections report on the results of the project for FY99.

Field Test Data Management for Grid-connected Systems

Status

Metlakatla System

Gridwise Engineering Company was contracted to develop a database suitable for analyzing one of the grid-connected systems, a 1-MW BESS, which was commissioned in February 1997 by Metlakatla Power & Light (MP&L) for the purpose of stabilizing its electrical grid and reducing its dependence on costly diesel generation. MP&L is a small stand-alone electric utility located on Annette Island in southeast Alaska. Its generation assets include four hydroelectric units, which together produce 5 MW, and a 3.3-MW diesel unit used primarily for load following and system stabilization. The BESS promised to eliminate the need for the diesel by following sharp load swings introduced by a local saw mill.

Historical performance data for the MP&L system included 171 BESS data parameters and 73 utility parameters that originated from two Supervisory Control and Data Acquisition (SCADA) systems. The data were available in a compressed, proprietary format on archive tapes. Data were converted to a usable format using software tools obtained from the SCADA software developer and in-house programming. The resulting electronic database was submitted as a project deliverable covering about two years of BESS operation.

A typical hour of operation for the BESS is shown in Figure 2-18. These data represent one-second samples between the hours of 9:00 and 10:00 a.m. on July 1, 1998; a special comma-separated variable (CSV) file was created for this purpose using HistData from the station control log files.

The total utility load is shown as the aggregate of all plant output including the BESS, Chester Lake, and two Purple Lake units (the third Purple Lake unit and the diesel were not operating). The BESS is shown charging and discharging at about the 0-kW level, and supporting the rapid load swings of the utility.

BESS performance data corresponding to this hour were extracted from the BESS log files and are shown in Figure 2-19. It is of interest to note that the string voltage and SOC remain fairly constant while the power delivered to the grid fluctuates significantly. During the course of the hour, the hydro unit's output rises and falls in such a way that the SOC remains at about 90%. Thus, while the BESS responds to instantaneous fluctuations, serving the load and keeping the frequency in check, the hydro units ultimately carry the stable load.

Likewise, the BESS is able to provide voltage stability by rapidly varying the kVAR output. The BESS is near the utility's load center and is controlled based upon voltage measurements taken at the Centennial Plant.

After the final CSV file was created, it was easily loaded into MS Access to create the database. This database is a project deliverable, and was standardized as was agreed to at a project review Meeting in Walnut Creek, California, on June 24 and 25, 1999.

The goal was to provide the parameters listed in Table 2-20 as a standardized format common to all four projects. However, not all of the parameters were available as shown in the table. In consultation with SNL, it was agreed that the operation of the Metlakatla BESS did not correspond to clearly defined cycles since the battery was always held at 90% SOC.

Furthermore, the only equalization charge performed was at startup, and this data and initial months of operation were not available. Therefore, even by arbitrarily defining a cycle (for example, based on reversals of DC current), the battery is never returned to full charge, the cycle count is unknown due to missing data, and there is no overcharge.

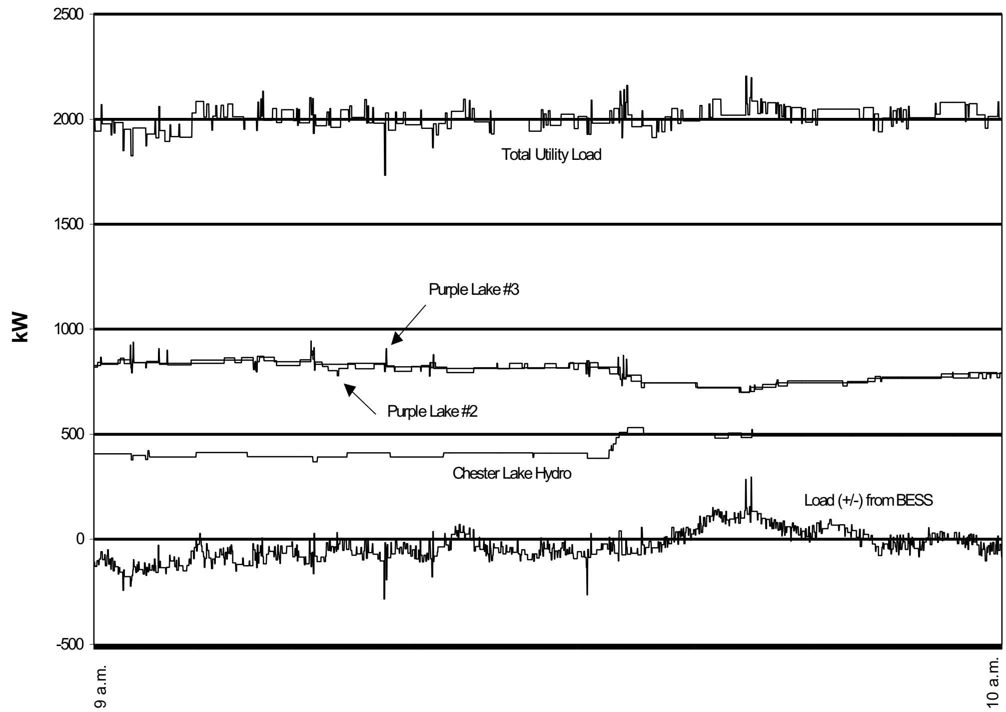


Figure 2-18. MP&L Power Plant Output Including BESS between 9 and 10 a.m. on July 1, 1998.

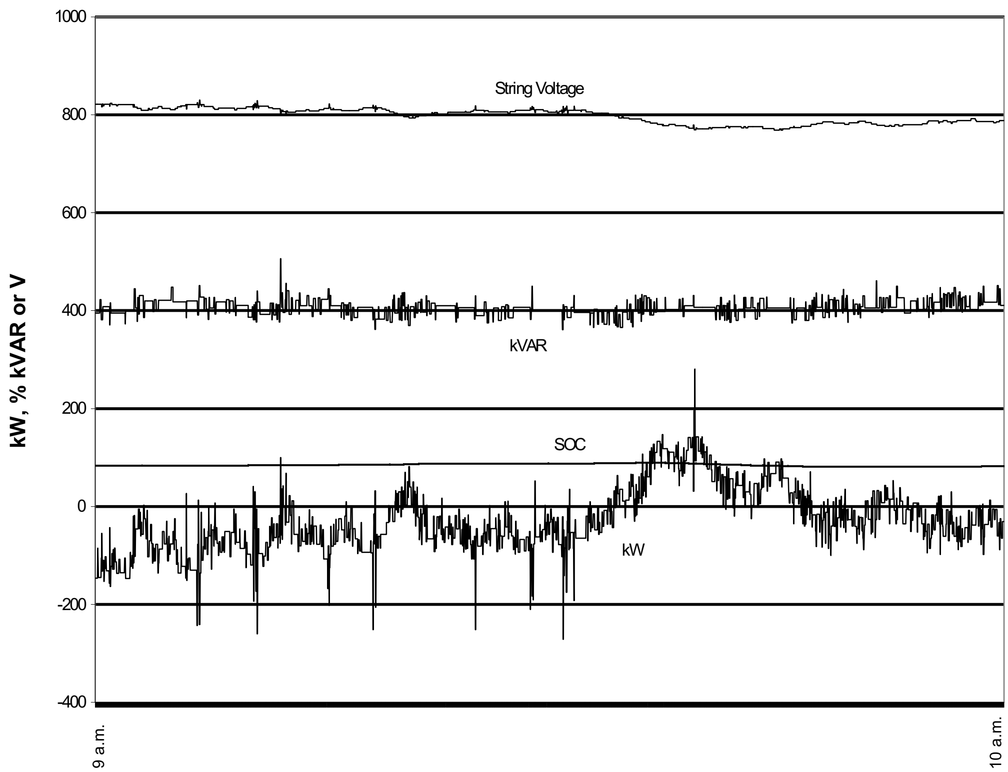


Figure 2-19. BESS Operation between 9 and 10 a.m. on July 1, 1998.

Table 2-20. Database Parameters

Parameter	Included?	Comments
Cumulative Ah (+ and -)	Yes	
State of charge (SOC)	Yes	
String voltage	Yes	
Overcharge (%)	No	No clear cycle definition.
Duty cycle count	No	No clear cycle definition.
Cumulative Wh (AC & DC)	No	No integrating transducer available.
System power (AC)	Yes	
Current (DC)	Yes	
Sample cell temperature	Yes	

In addition, the SCADA system did not include integrating watt-hour transducers, either on the AC or DC side. While it would be possible in theory to estimate cumulative watt-hours based upon amp-hour and string-voltage measurements, the results would be subject to considerable uncertainty due to missing data. Missing amp-hour data present no problem since the integration was performed at the transducer level. However, there was no transducer that integrated voltage.

In addition to the missing data, a practical problem arises. The technique for creating CSV files results in instantaneous (not averaged) data in the 10-minute intervals. While this may be sufficient for slow-changing or time-integrated parameters, it leads to difficulties in reporting data for rapidly changing data.

For example, BESS power output fluctuates on a sub-second basis; hence 10-minute snapshots are an insufficient basis for integrating watt-hours. While it is possible to create CSV files on a millisecond basis, it would be impractical to integrate values using this technique since the maximum amount of millisecond data that HistData could produce would be under five seconds. The CSV files would have to be manually created for each five-second interval for the two-year time span.

In considering the errors introduced by missing data and dead band resolution, coupled with the impracticality of manually integrating voltage over time, it was determined that watt-hour data could not be provided with the database.

The deliverable was provided on an accompanying disk to SNL, and included the files shown in Table 2-21.

An economic analysis was performed using actual cost data and conventional planning practices. Key economic impacts include the following:

- **Load Following**. The BESS provides load following service, nearly eliminating the operation of the diesel generator set. This saves about 450,000 gallons of fuel/year and reduces the net staffing requirements by 3.75 “full time equivalent” technical positions.

- **Reserve Generation Capacity**. The BESS defers the need for additional reserve peaking power throughout its design life of 10 years.

- **Voltage Regulation**. The BESS defers investment in two 450-kVAR switched capacitor banks.

- **Customer Claims**. The BESS reduces voltage transients on the distribution lines, saving costs of damaged customer equipment.

Results of the economic analysis are presented in Table 2-22. The actual benefit/cost ratio is calculated as 1.97 relative to conventional resource planning, and the payback period is three years.

It is important to note that the primary benefit provided by the MP&L BESS is system stability. This is possible since the total capacity of the BESS (1.6 MVA for 10 seconds) is as high as 40% of the total peak load. Even the continuous rating of the BESS (1.0 MVA) represents a significant portion (25%) of the peak load.

For the economic results encountered at MP&L to be replicated elsewhere, a BESS of comparable proportion will have to be specified. As a practical matter, the ideal location will be small island grids. The optimal sizing of the BESS would be determined based upon utility-specific parameters.

As a result of this project, several recommendations were made for follow-on work, and they include:

- Conducting a detailed performance analysis based upon the converted historical data;

Table 2-21. File Descriptions of Electronic Deliverable

Filename	Description
metlakatla1.mdb	MS Access database
/ALG Files/*.ALG	Time-stamped status information and alarms (text)
MetDataExtractor.xls	MS Excel spreadsheet and macro used to create CSV files from 32-bit historical log files.
Points List Rev 6.xls	Electronic version of “Appendix A–Points List,” of the final report.
BESSDBDump.csv	Comprehensive list of all InTouch tags, including alarms and measured data, alarm setpoints, and other information pertaining to the BESS SCADA system.
UtilDBDump.csv	Similar file pertaining to the Station Control SCADA system.

Table 2-22. Overall Cost and Benefits from BESS in Metlakatla System

	Conventional Generation	BESS	Net Benefit (Cost)
Load following	$3,869,811	$0	$3,869,811
Reserve generation capacity	400,000	154,217	245,783
Voltage regulation	25,605	8,095	17,510
Customer claims	30,723	0	30,723
BESS operations	0	93,705	(93,705)
BESS capital	0	2,022,727	(2,022,727)
Total	$4,326,140	$2,278,745	$2,047,395

- Converting recent historical log files archived at Metlakatla;
- Determining the feasibility of interconnecting the MP&L network to the larger Ketchikan Public Utility (KPU) grid, thereby utilizing the BESS for system stabilization and peaking power;
- Characterizing the overall market for the island-grid stabilization application at rural electric cooperatives in the United States;
- Designing and installing a server at MP&L to provide real-time data access and visualization over the internet; and
- Developing a database server at SNL for providing Internet access to historical data.

Brockway Standard System

Energetics, Inc. was contracted to develop a database suitable for analyzing the other grid-connected system that was included in this study, a 1-MW/10-second power-quality system at the Brockway Standard Lithography Plant in Homerville, Georgia (Figure 2-20). A team from SNL, Energetics, and Gridwise Engineering visited the Brockway plant on May 5, 1999, to learn more about the operations and the performance of the PQ2000.

The plant operates four production lines, two of them seven days a week. Labels are printed directly onto sheet metal that is formed into cans for food, chemicals, and specialty products (i.e., Folgers coffee, Eagle Snacks, Guy Foods, and Thompson Water Sealer) at Brockway can plants. Output averages 73.5 sheets per minute when production lines are operating (roughly 40% or 10 hours of every 24-hour day). Brockway is a full-service shop, capable of handling artwork (label design and plate preparation at subsidiaries) and X-ray plates and screens processed on-site at Homerville.

Between 1994 and 1995, on the advice of Oglethorpe Power Corporation, Brockway invested almost $600K to upgrade many of its motors that were near their end of life and to install adjustable-speed drivers (ASDs) and Omegapak adjustable frequency controllers to control all of the motors throughout the plant. The ASDs are very sensitive to power glitches that stop production lines.

Figure 2-20. Brockway Standard Lithography Plant.

There are approximately 16 motors per production line. In addition, there are motors driving the solvent disposal, incinerators, and other operations. Most of the equipment at the lithography plant dates back to the 1950s. Electricity, natural gas, and occasional propane purchases satisfy the energy requirements of the plant. Slash Pine, the local energy cooperative, is Brockway's electricity provider, which is one of the 39 electric membership corporations that formed Oglethorpe Power Corporation in 1974.

Installation of the PQ2000 was initially estimated to cost $500K, but total costs through start-up reached $1M. Brockway and Slash Pine were minor financial contributors ($32K each) while Oglethorpe Power Corp, Georgia Power, and EPRI shouldered most of the cost to install the PQ2000. In 1997, Oglethorpe restructured into three companies, and EnerVision, the new customer service company, was interested in selling the PQ2000 to Brockway. The lithography plant was not in a financial position to purchase the unit. In the end, Oglethorpe (EnerVision), Omnion, EPRI and Georgia Power agreed to let Brockway keep the PQ2000 unit; Omnion maintains the DAS.

The system consists of a main system container that houses the batteries, a power controls cabinet that contains an electronic selector device (ESD), and an isolation transformer (Figures 2-21 and 2-22).

The Data Acquisition System

Omnion co-developed the DAS with Delphi Energy and Engine Management Systems. The system has operated since the PQ2000 was tested in the factory and continued operating when the battery was installed at Brockway in July 1996. The battery system became fully operational in mid-December 1996. The chronology is important because not all counters in the software were properly reset as the system entered operation.

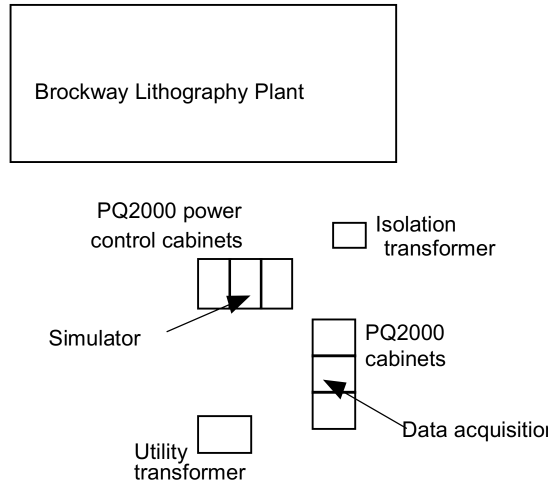


Figure 2-21. Layout of PQ2000 Installation (not to scale).

Figure 2-22. PQ2000 Located behind Brockway Plant.

With the help of Omnion, Energetics remotely accessed and downloaded data from the PQ2000. The data from May 1996 (factory testing) through July 1999 were consolidated in a Microsoft Access database built by Energetics. The testing phase continued from May through December 1996. The first trigger event (charge) occurred on December 8, 1996, but the first discharge did not occur until January 1997, which was chosen as the starting date for analysis of the battery's operation because all previous events occurred during the battery system's testing phase. The testing phase data are included in the database, but not analyzed for the reporting process. Although July 31, 1999 was chosen as the cut-off date for the data analysis, Energetics continues to monitor and collect data.

The remote access process included the capability to download data remotely from the PQ2000 DAS at

Brockway. The DAS is housed in one of the two containers sitting on concrete pads outside of the plant. Figure 2-23 shows the screen and keyboard sitting on the base of the cabinet, and Figure 2-24 shows the industrial processor that drives the DAS. A Windows95 remote access package called ReachOut is used to connect to the computer and transfer data.

Figure 2-23. PQ2000 Host Computer.

PQ2000 Technical Performance

Energetics performed some preliminary analysis on the PQ2000 database. The results are presented below. More time is needed to develop appropriate queries to answer additional questions about the technical performance of the PQ2000.

Figure 2-24. PQ2000 Industrial Processor.

The line disturbance event data was queried to determine frequency of discharge events per season and per time of day in 1998 for recorded events only and recorded with modified and unrecorded events (see Figures 2-25 and 2-26). In 1998, there were 69 recorded discharges and 144 total discharges (recorded, modified, and unrecorded events). Examining 1998 recorded discharge events revealed that the majority of events (62%) occurred in the summer months (June-August) while 25% of the events occurred in the fall (September-November). This is expected since the majority of voltage disturbances occur in the spring and summer because of the frequent occurrence of lightning storms. In 1998, the spring was mild in the south. The situation is the same when the unrecorded events are included.

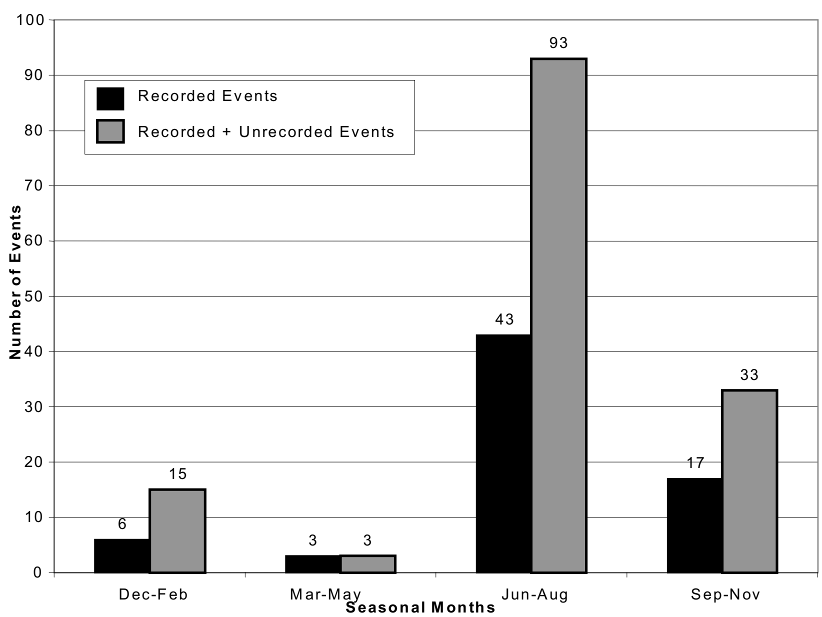


Figure 2-25. PQ2000 Discharge Events by Season in 1998.

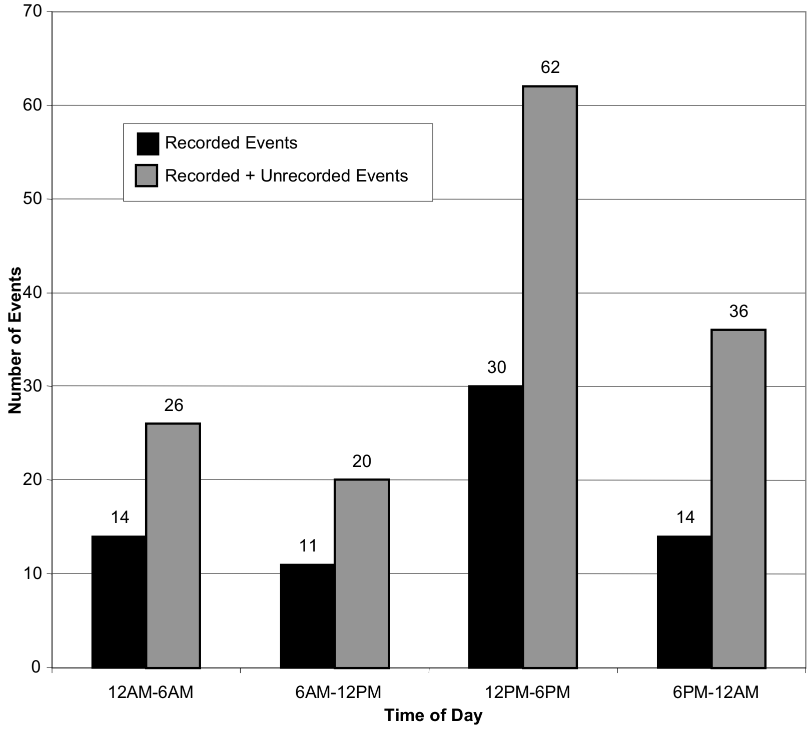


Figure 2-26. PQ2000 Discharge Events by Time of Day.

The line disturbance analog data table was also queried to determine the time-of-day prevalence of discharge events. The majority of lightning storms in the Homerville, Georgia, area occur in the afternoon. This is reflected by a 44% frequency of recorded discharge events from 12:00 p.m. to 6:00 p.m. All other line disturbance events were spread out fairly equally among the other time periods. Including unrecorded events reinforces this time-of-day prevalence. The cumulative values for the PQ2000 operation at Brockway (December 1996 through July 1999) are presented in Table 2-23.

Table 2-23. Cumulative Values for PQ2000 Operation at Brockway: December 1996 through July 1999

Variable	Value
Total number of duty cycles	106
Recorded discharge output	12.4 Ah
Modified discharge output	30.2 Ah
Discharge output with modified and unrecorded events	58.8 Ah
Normal charge input	1,755 Ah
Equalization charge input	2,522 Ah
Charge input	4,267 Ah

Figure 2-27 shows the recorded Ah discharged from the PQ2000 and the estimated Ah discharged over a two-month period. Since discharges shorter than 0.04 seconds are recorded as a discharge of zero amp-hours, Energetics did a second calculation estimating the Ah discharged during these events. Also, included in this graph is the estimated, modified, ampere-hours for missing events. Energetics estimated the amp-hours missed during these events and added them to make a final estimate of the amp-hours discharged by the PQ2000. As shown in Figure 2-27, the total estimated amp-hours discharged can be three times as much as the actual recorded data.

Figure 2-28 shows the current versus time for the year 1998. Current fluctuated between 400 and 1,100 A during this year. This is typical for all operational data. In 1998, June experienced the most current fluctuations due to the greater number of discharges in that month as compared to the rest of the year.

Figure 2-29 shows the comparison of duty cycle charge input with both modified (zero Ah replaced with 0.02) and modified plus unrecorded events. Due to the magnitude of all normal charges into the PQ2000, this parameter is not displayed in this graph. However, the difference in normal versus duty cycle charges in 1998 can be viewed in Figure 2-30. Normal charge input represents PQ2000 battery charges that follow all

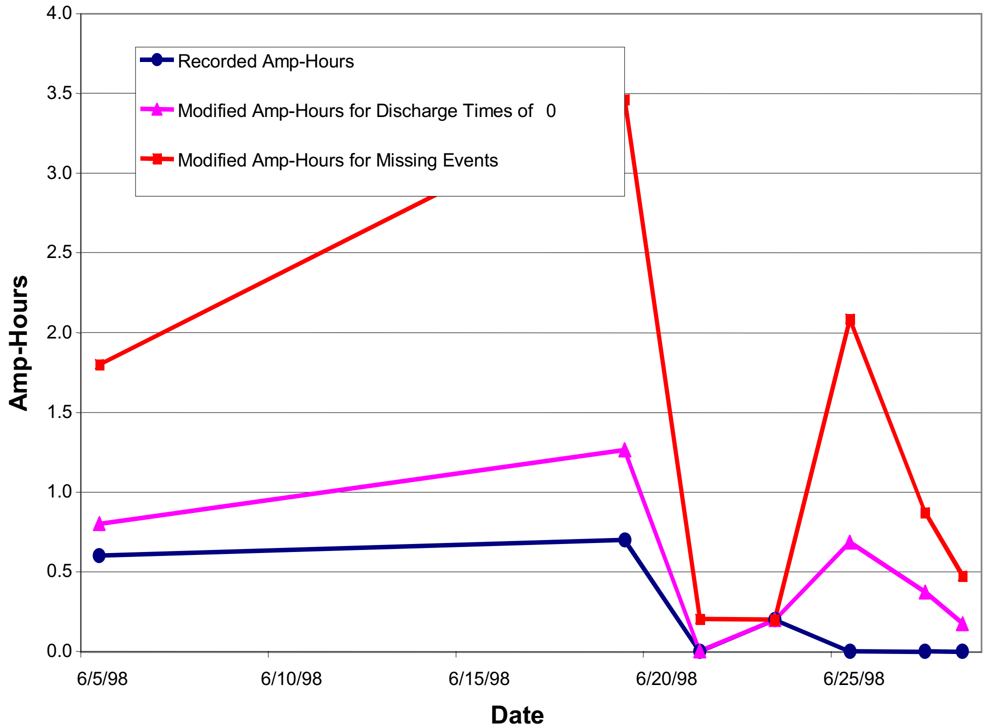


Figure 2-27. Brockway PQ2000 Discharge Ampere-hours Comparison in June 1998.

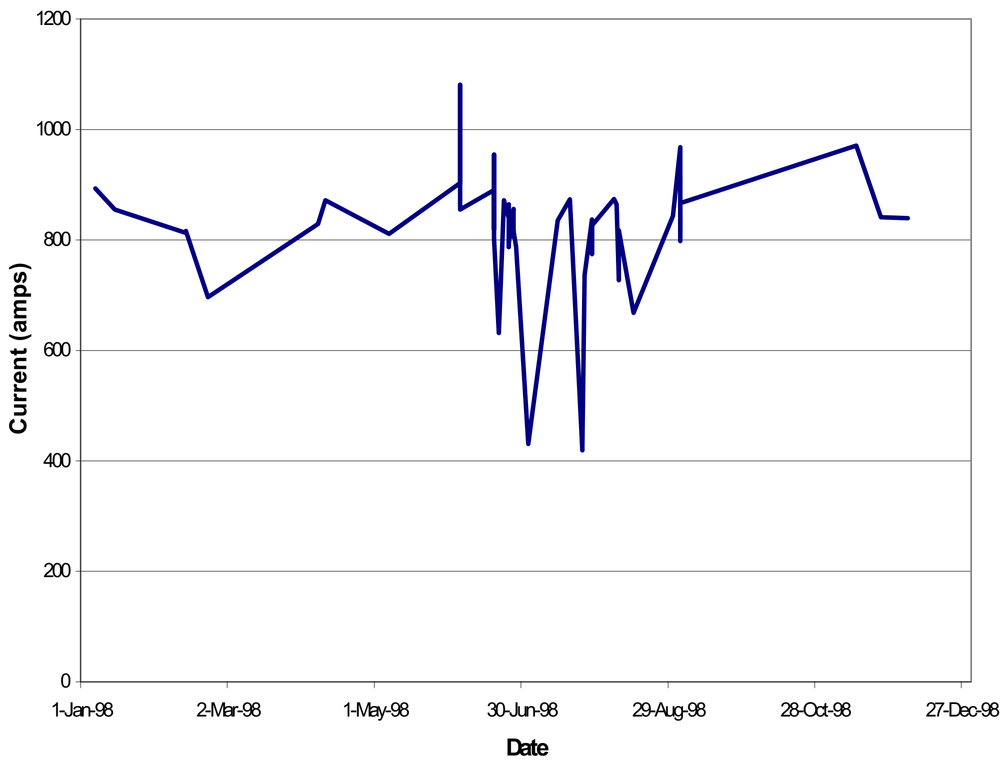


Figure 2-28. Brockway PQ2000 DC Current Versus Time in 1998.

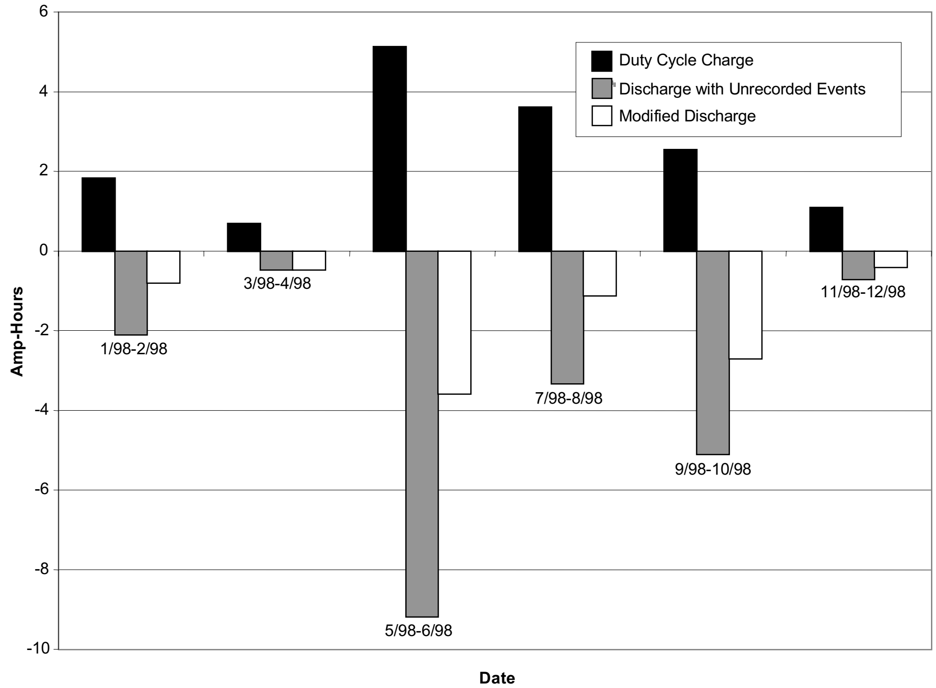


Figure 2-29. Brockway PQ2000 Charge and Discharge Comparison in 1998.

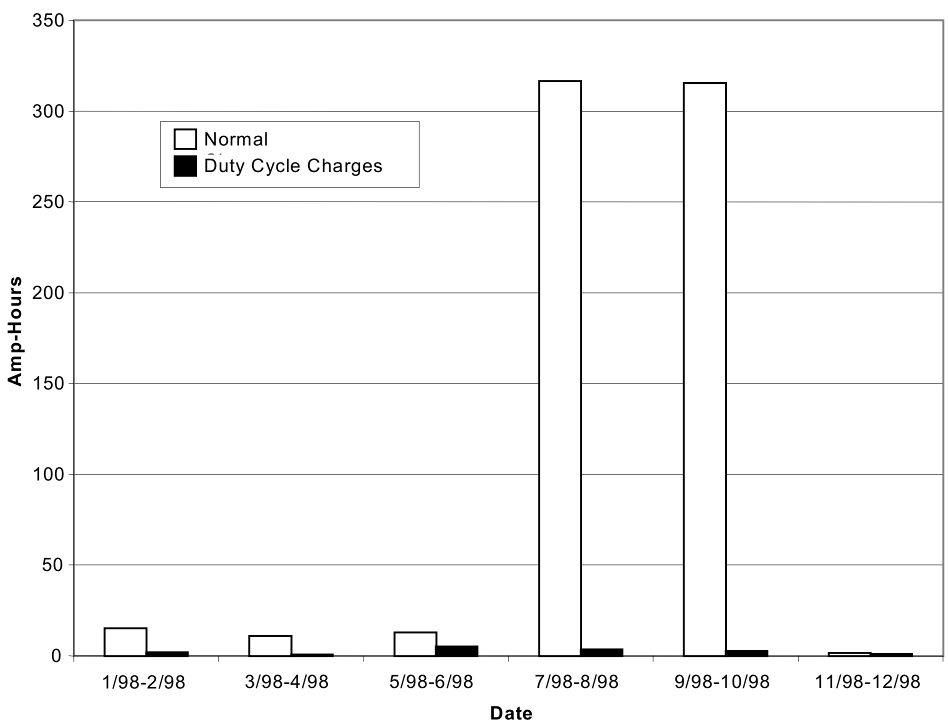


Figure 2-30. Brockway PQ2000 Normal Versus Duty Cycle Charges in 1998.

recorded and unrecorded discharge events as well as normal charges that were performed on the system. In the months of July through October, normal charges exceeded 600 Ah. These months contained the most recorded and unrecorded discharge events. Out of the total 144 recorded and unrecorded discharges, 60 events occurred in July through October.

As Figure 2-29 shows, the duty cycle charge input is a better reflection of Ah into the PQ2000. It was expected that charge input would be greater than discharge output. However, discharge Ah that includes unrecorded events exceeded duty cycle charges in several months (January/February, May/June, and September/October). It appears that by neglecting the unrecorded discharges, a more expected charge-to-discharge ratio is achieved. This supports the assumption that the unrecorded line disturbances occurred while the PQ2000 was already discharging.

PQ2000 Economic Performance

This economic performance analysis is based on empirical data from PQ2000 operation, cost estimates from Brockway Standard, and information from equipment suppliers. The Square D Omegapak ASDs are considerably more sensitive to power glitches than the motors they control. These ASDs will fault during outages of 0.2 seconds or greater. Of the 158 recorded discharges that occurred during the 32 months of PQ2000 operation, 96 events were longer than 0.2 seconds in duration. These events are the basis for the economic performance assessment.

These ASD faults cause a variety of jams in the production lines that can result in significant downtime. They are shown in Table 2-24 and described in more detail in the final Energetics report.

Table 2-24. Brockway PQ2000 Downtime Causes and Duration

Types of jams	Off-line time (minutes)
ASD synchronization–minor	15
ASD synchronization–major	30
Press jam–minor	20
Press jam–major	30
Oven jam–minor	45
Oven jam–major	60
Incinerator cleanup	30

The Brockway manager estimates that each hour of production that is lost costs the plant $275, including labor and materials. By applying that value to the downtime estimated for the four types of jams avoided since the PQ2000 became operational, the yield is $27K (Table 2-25).

The cumulative costs avoided by the PQ2000 are estimated to be $168K over the 32 months of its operation, or $63K annually. When these avoided costs are compared to the financial stake of Brockway in the installed cost of the PQ2000 ($32K), the economic benefits far outweigh the costs. If reasonable annual maintenance costs of $18K are assumed, the system economics are still attractive. The key missing ingredient is in the cost of electricity, which is unknown. Further investigation is needed to determine the lithography plant's share of the total Brockway electricity bill with the Slash Pine cooperative.

If the full installed cost of the PQ2000 is considered, approximately $1M, then the benefits do not justify the installation. Energetics had hoped that an

Table 2-25. Summary of Glitches Avoided by Brockway PQ2000: December 1996 through July 1999

	Simple	Typical	Environmental	Outage	Total
Number of events	50	36	4	6	96
Hours off-line	12.5	57	4	24	97.5
Lost production $	3,400	16,000	1,000	7,000	27 K
Additional costs $					140 K
Cumulative costs $					168 K
Annual costs $					63 K

alternative system (e.g., UPS) could be examined to determine how the PQ2000 fares, but Brockway insists that it would never have purchased an alternative system.

Field Test Data Management for Renewable Generation and Storage for Off-grid Systems

Renewable generation and storage (RGS) systems for remote power applications represent a sizable, high-value market for the introduction of renewable energy into the United States and the world economies. BESSs are a key component to the reliable and effective functioning of RGS applications. The white paper titled *Renewables and Energy Storage: Characterization of Initial Projects and Emerging Opportunities for Hybrid Power Systems* provided an overview of several domestic and international RGS Projects using BES components. This task determined a method for archiving, summarizing, and reporting data from these and other field tests and began the process with data from two field tests. The operational characteristics of interest include, for example, battery, capacity, type, charge/discharge strategy, operating data, life, cell failures, maintenance provisions, and safety precautions. Data collected from systems like the Arizona Public Service (APS) Solar Test and Research (STAR) Test Facility could be included in this project activity.

The ESS Program and the contractors involved in the data management project selected two sites and have performed the data analysis. The two off-grid systems both have renewable generation resources.

Status

Wawona Point Off-Grid Power System

Endecon Engineering was contracted to develop a database suitable for analyzing one of the off-grid RGS systems. This is a summary of the results of the preliminary database development and analysis project. Over the course of six months, Endecon developed a number of analytical tools using Microsoft Access 97 and Excel 97, and evaluated data from the Pacific Gas & Electric Company (PG&E) Off-Grid Power System (OGPS) located at Wawona Point in Yosemite National Park. These preliminary results are intended to provide direction for further database development that will lead to a more standardized data collection and analysis process for existing and future RGS systems.

The approach on this project was to focus on the development of database tools and investigate how they could be used to describe the performance of a fairly well known system. Despite Endecon's direct involvement in the OGPS Project over its life, there were many unexplained events and operational quirks that make it an interesting system to analyze.

The OGPS is a self-contained, PV/propane hybrid, AC power system that was developed for PG&E's Research and Development Department. Major system components are listed below:

- 1080-WSTC, DC PV array (18 each, Solarex MSX-60 Modules)
- 5-kW 120-Vac propane generator (Onan 5CCK)
- 16-kWh VRLA battery bank (4 each, GNB 3-75A27)
- 4-kW Inverter (Trace SW4024)
- 50-A PV charge regulator (Solar Engineering PPS-50-24)

The OGPS is located about 100 feet west of a helipad on a mountain peak known as Wawona Point about 10 miles east of the south entrance of Yosemite National Park (Figure 2-31). The peak overlooks the Wawona Valley from the south. A two-way radio repeater used for emergency and operating communications within the park is located about 50 ft east of the helipad. A television translator is located several hundred feet to the northwest of the helipad, which provides TV signals to several buildings and residences in the valley below. Utility power (240-Vac) is supplied through a cable running up the slope from a utility transformer and revenue meter located about 0.5 miles

Figure 2-31. OGPS at Wawona Point in Yosemite National Park, Consisting of a 1080 PV Array, 16-kWh/24-V VRLA BESS, a 5-kW Propane Generator, and a 4-kW Inverter.

west of the helipad. While there is a road to the site, it is snow-bound during the winter, accessible only by foot or by snowcat.

The radio-repeater and television translator each require about 5 kWh/day. Taken together, this is twice the design capacity of the OGPS (ignoring the reduced available irradiance at the selected site compared to the design). The radio repeater is a critical element of the Park Service emergency communications system. It includes its own battery bank; AC power is rectified to float the battery and power the radio. In the past, when there were utility line failures, Park Service personnel would install a small generator at the radio and hope that the PG&E line would be repaired before the generator ran out of gas and the backup batteries were depleted. It was decided that the OGPS would be used to power the radio transmitter only, leaving the TV translator utility connected. It was also determined to connect the utility to the Trace inverter to allow sellback of excess solar generation and would provide a secondary backup to the PV and propane generator because there was some uncertainty about both the load and the solar resource (especially the effect of shade from the trees).

The OGPS system was monitored with a Campbell Scientific Inc. (CSI)-based DAS. A CSI 21X datalogger measured 14 analog channels, including two differential measurements and 12 single ended measurements, as shown in Table 2-26. The datalogger sampled the input channels once every second and recorded totals and averages every 10 minutes. Table 2-27 shows the raw data as it was stored in the database. The ambient temperature thermocouple was located behind the array. Its position, sometimes in direct sunlight, and lack of radiation shield, caused it to read higher than expected. On July 18, 1996, the thermocouple was glued to the back of one module thus providing module temperature from that point on.

Recorded Data

A brief review of various summary plots of the data offers insights into the operation of the system, as well as some surprising consequences of normal data processing techniques.

Figure 2-32 shows daily average maximum and minimum battery currents (the average is a tick mark, and the minimum-maximum range is shown by a vertical line). The first winter/spring of low-battery transfer operation (use utility as last resort) showed regular high-charge currents as the generator had to kick in every few days to recharge the battery. The following summer/fall of float mode operation showed very little discharging or charging.

Table 2-26. Wawona Point OGPS CSI 21X Datalogger Input Channels

Input Channel	Description
1H	Array current (V Diff)
1L	″
2H	Battery current (V Diff)
2L	″
3H	POA irradiance
3L	Generator status (Off=1, On=0)
4H	Load power status (On=1, Off=0)
4L	Generator current
5H	Load voltage
5L	Utility voltage
6H	Load current
6L	Utility power
7H	Load power
7L	Ambient or module temperature
8H	Battery temperature
8L	Battery voltage

Figure 2-33 shows the potential error between two ways of recording battery charging current. The simplest way is to record a single bi-directional current value, with positive data representing charging and negative data representing discharge. However, since the recorded data are average values over an interval of time, it is certainly conceivable that for a portion of an averaging interval the battery might charge, while, for the remainder of the interval, it could discharge. If the charge and discharge amp-hours were similar, the net average current would be zero. This loss of information would be significant both in loss of knowledge about extreme current levels, and regarding integrated quantities such as charge and discharge amp-hours. Since this data set includes separate battery-power-out and battery-power-in output fields, we can estimate average battery-discharge-current and average battery-charge current. It is straightforward to simulate a bi-directional output using this data. This figure presents the error between computing the daily discharge amp-hours both ways. If there was any average discharge current, then when the net current is charging, the error will be 100%. While this figure demonstrates that the error can be quite large while the battery is floating, it also shows that significant errors (>10%) can show up even during periods of time when the system appears to be cycling regularly.

Table 2-27. Wawona Point OGPS Database Field Description

Field	Label	Units	Description
1	Array ID		=101 (defines section of code that generated output)
2	Year		Four digit year
3	Day		Day of year (1 – 366)
4	HHMM		Time of day (0 - 2400)
5	# of Samp		Number of samples in the average
6	Vac Load	Vac	Inverter output voltage to load
7	Vac Util	Vac	Voltage supplied by utility
8	Iac Load	Iac	Inverter current supplied to load
9	Pac Util	Wac	Power supplied by utility
10	Pac Load	Wac	Inverter output power supplied to load
11	Iac Gen	Iac	Generator output current
12	TUtil		Number of samples during which the utility was supplying power
13	TGen		Number of samples during which the generator was running
14	Vdc Bat	Vdc	Battery voltage
15	Pdc Bat Chg	Wdc	Power supplied to battery
16	Pdc Bat Dis	Wdc	Power provided by battery
17	Pdc PV	Wdc	Power provided by PV array
18	Gen Status		Generator status (1 = Off)
19	Load Status		Load status (1=On)
20	T 21X	°C	Datalogger front panel temperature (enclosure internal temperature)
21	Tamb/Tmod	°C	Ambient temperature 1/16/96 - 7/18/96 Module temperature 7/18/96 - present
22	TBat	°C	Battery temperature
23	Irr POA	W/m^2	Plane-of-array irradiance
24	Vdc 21X Bat	Vdc	Datalogger battery voltage

Figure 2-34 shows a close-up of one week of charge and discharge currents. Apparently, the generator had difficulty starting and staying started. The Park Service was supposed to have sent someone to adjust the generator, but it is not clear from any recorded communications what the conclusion from that inspection actually was. In any event, while this is not an ideal operation, it is real operating data that would have been 10% in error if a single bi-directional current value had been recorded. In addition, interpreting the odd charging current is simplified when the current charge and discharge data are separate.

The SOC algorithm used to generate the SOC and overcharge results was based on an ampere-hour counting technique with manual and automatic SOC resets (points at which the algorithm concludes that the SOC is 100% and discards any accumulated error). This algorithm was developed as an attempt to account for SOC carryover from one partial charge cycle to another.

In a controlled charging environment, a battery is considered at 100% SOC when it is at a specified float voltage level and the current into the battery is below a threshold value. The battery discharge amp-hours may then be accumulated, and counted against the amp-hours required to restore the battery to the original voltage and current levels. Additional charging amp-hours required to restore the battery to its original state may be quantified and used as an alternative indicator of complete charging.

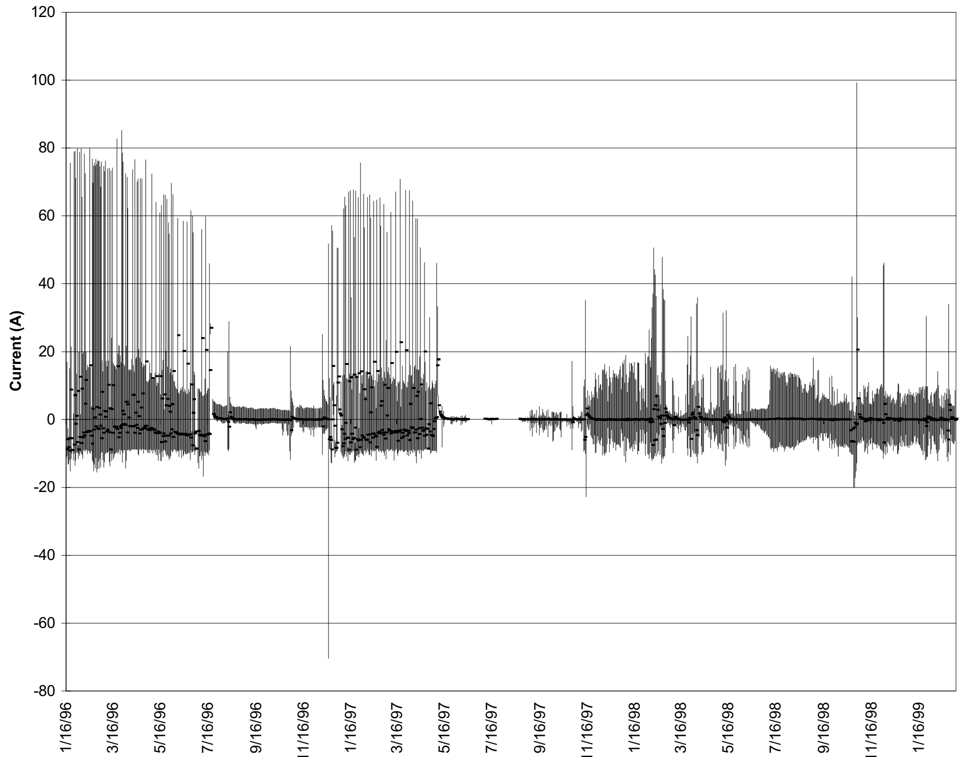


Figure 2-32. Wawona Point Daily Battery Current.

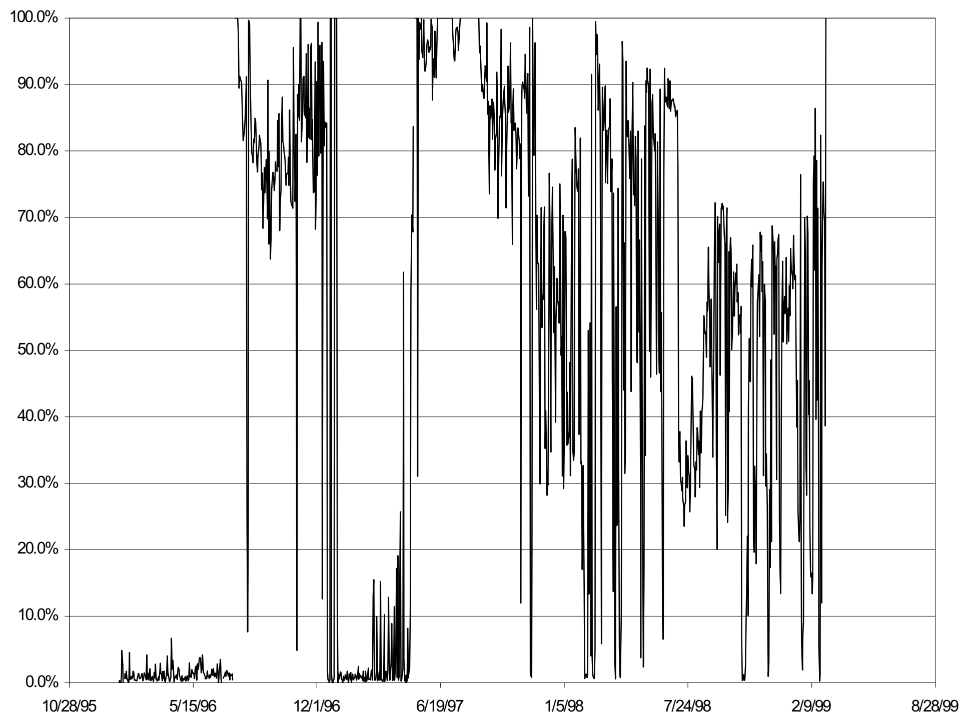


Figure 2-33. Wawona Point Daily Discharge Amp-hour Error.

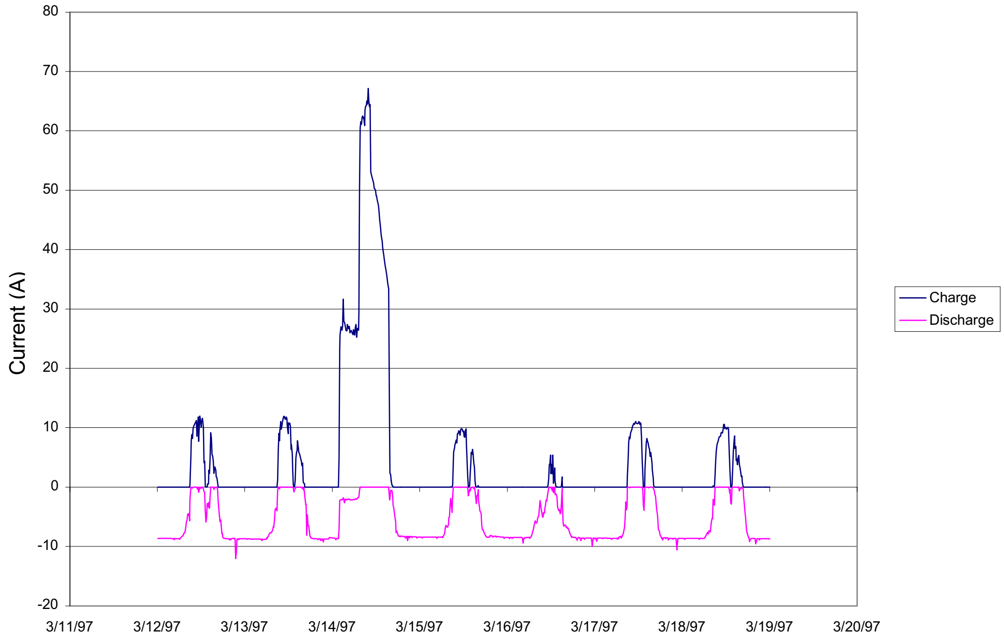


Figure 2-34. Wawona Point Sample of Rapid Charge and Discharge Cycling Current.

In an uncontrolled charge as well as discharge regime, the battery may not return to a full charge for an extended period of time. Estimating absolute SOC during such an extended period remains a challenging problem, but at least it is clear that the SOC value at any time is a composite function of the charge and discharge influences it has experienced since the last time at which the SOC was known.

The first iteration of this algorithm counted amp-hours and assumed that if the battery voltage exceeded a preset value (temperature-compensated) then, when the voltage dropped below that value again, the SOC was reset to zero. While this algorithm appeared to provide reasonable results, it lacked a reasonable theoretical justification.

The algorithm actually used here is based on discussions with a member of the Sentech team, in which the onset of a discharge that occurs after the minimum overcharge threshold has been reached causes the SOC reset. The theoretical basis of this comes from the assumption that a limited number of charge sites need to be recharged before the battery is fully charged. Once this is assumed, any measured charge in excess of this overcharge value is certain to be wasted. The algorithm maintains a single SOC value that is split into a presentation SOC and an overcharge value for reporting to the operator.

In addition to the automatic SOC resets, a semi-automated method for handling extended gaps in the data was also used. The SOC estimate accumulates with each data record, and gaps of more than some maximum interval of time (1.5 hours in this case) must be handled specially. This mechanism allows the SOC to be estimated in one of several ways after an extended period of missing data: set to a specified value, maintained the same as before the missing data, or linearly extrapolated with an analyst-specified SOC rate-of-change.

Figure 2-35 shows the resulting average and range of SOC estimates for each day in the data set. The SOC appears to drift downward during the low-battery transfer mode (which simulates not having a utility grid by using it only as a last recourse). It is likely that the lack of temperature compensation is causing the bulk charge cycle to terminate too early.

A tripped breaker with the inverter in low battery transfer (LBX) mode on May 6, 1997, caused the inverter to draw the battery down to the low-voltage-disconnect level. When the breaker was reset and the inverter switched to float mode, the inverter recharged the battery over a 16-hour period. This recharge required 962 Ah. This is a little low when compared to the manufacturer's rating of 975 Ah. Since the cumulative SOC estimate had dropped to −24% prior to the recharge, it appears that the algorithm had drifted low by about 24%.

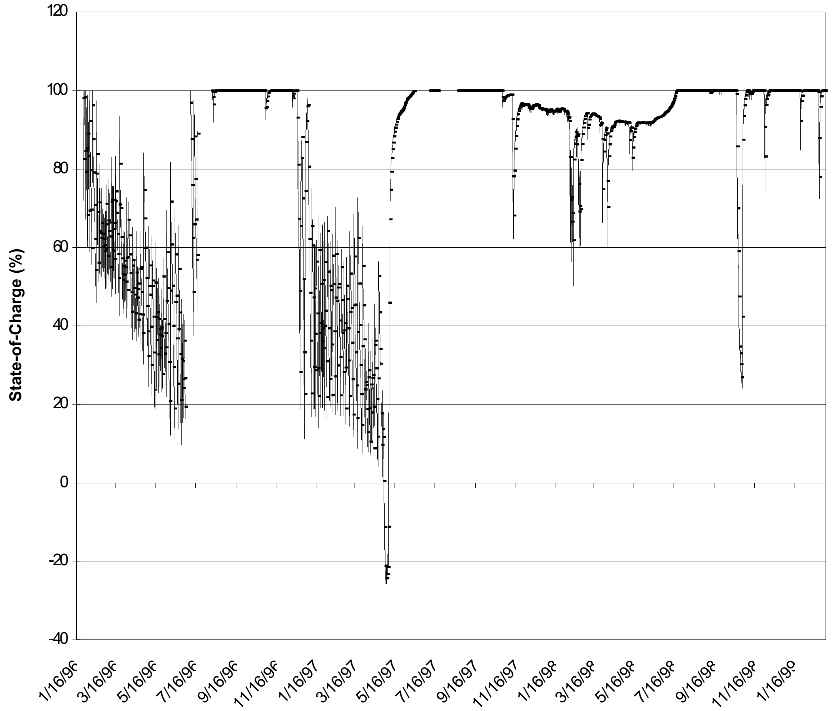


Figure 2-35. Wawona Point Average Range of Daily SOC.

A similar event on October 28, 1998, lead to a recharge that took a few days and included a couple of brief discharges (50 Ah) with a net charge of 720 Ah. However, this event followed 19 months of float at low (temperature-compensated) voltage, so the actual charge available in the battery at this point was probably somewhat reduced.

It appears that the SOC algorithm, as currently implemented here, suffers from a downward drift during partial cycling, and shows an upward drift during float operation.

In summary, the primary goal of this task was to build a tool for evaluating storage system characteristics and building a standard database of performance data for the OGPS system located at Wawona Point. In this regard, significant progress was made in developing the basic processing scheme and streamlining the review of the resulting data.

The resulting data analysis tool contains a semi-automated process of extracting data from the source-table and storing the cumulative results into the standard database. In addition, tabular and graphical review of the data in daily aggregate and controlled time intervals is quick and efficient, using the versatile Excel spreadsheet software as a rapid evaluation tool.

The secondary goal, that of analyzing the results to obtain conclusions regarding the present and continued operation of the OGPS system had somewhat more limited success. The weakly controlled cycling characteristics of this system, in its off-grid mode of operation make comparisons with standard controlled cycling data challenging at best. Limitations in the data quality and even a missing power-flow measurement prevented generation of a complete and accurate standard database.

The key measure of battery health, SOC, is difficult to estimate from real-world data with incomplete charge cycles, and it is no easier to estimate during float operation. Missing data is both a real and significant impediment in this endeavor as well, requiring manual intervention and probably manual replacement in order to obtain reasonable results. This database implements SOC algorithm that attempts to evaluate SOC under real-world conditions, including analyst-specified adjustments. The database does not implement algorithms for filling in missing data or for flagging such data values in order to trace them back to the original data. Given the occasional periods where the data are "slightly wrong," source data correction will in general be required to obtain accurate results. Semi-automated procedures for finding data inconsistencies and repairing them will need to be implemented.

The battery charging voltage in this system was clearly too low during float mode, and was possibly failing to complete generator-driven recharge cycles as well, due to a lack of temperature compensation. The consequence of this poor float mode operation appears to be a reduction in capacity of as much as 25% over a 19-month period of float operation. If no change in operational settings occurs, this battery may reach end-of-life within the next two years. Changing the charge control to include temperature compensation should extend this life by several years, but it is not clear at this point how the system will behave when it is converted back to off-grid operation, since the SOC estimates computed so far for that type of operation are questionable.

Given the fact that this system requires regular generator run-time even during sunny periods when in LBX mode, this system is already undersized for the radio repeater load. If the existing system were to be effectively used to replace the utility entirely, the inefficient DC-AC-DC power conversion process should be eliminated and the PV array increased to handle low winter insolation. Eliminating the inverter will also eliminate the non-temperature-corrected charge control regime.

System analysis needs attentive system operators and good operational records. Because of the distribution of responsibilities and expertise between organizations and the minimal site-specific system design for this application, a number of operational quirks and system problems were accepted and ignored for extended periods of time.

Grasmere System

Sentech, Inc. was contracted to develop a database suitable for analyzing the other off-grid RGS system in this study. The site is located near Grasmere, Idaho, about 125 miles south of Boise (Figure 2-36). Major components are a PV array, battery storage, control systems, and backup diesel generators.

The Grasmere RGS installation supplies power for an Air Force training unit that provides electronic emission simulations for military aircraft. A crew from nearby Mountain Home Air Force Base staffs it.

The station is situated in mountainous terrain at 5800 ft and contains an office/communications building, a barracks, several storage/equipment buildings, high power radars and other emitters, water storage tanks, and a battery storage building. The power needs include housekeeping loads, for example, water tank freeze-prevention equipment, radars, and other electronic equipment. The peaks required for the electronic equipment are many times greater than those required for the basic housekeeping loads.

Figure 2-36. Location of RGS at Grasmere.

While Air Force personnel operate the station, the power system is provided under contract with Idaho Power Company (IPC), which is responsible for acquisition and maintenance of this equipment. The site is approximately 40 miles from the nearest power lines, and line extension was not a viable option. From the customer's viewpoint, the equipment currently installed has a good performance record; power shortages have not been a problem. The Air Force appeared to be satisfied with the cost and reliability of the power supply and the service provided by IPC. However, IPC expressed the opinion that the storage system has been "overworked" and that the replacement system should be significantly larger in storage capacity.

The PV array consists of 648 Solarex MSX120 panels, each rated to deliver 7-Ah at 17.1-V, or 120-W (peak output). Eighteen panels are electrically connected in series to provide a 308-V string, and 36 such strings are connected in parallel. The total field is rated at 252 Ah/308 V, or slightly over 77-kW peak output. Given the nominal battery voltage of 240-V, the 308-V PV output avoids the requirement for a DC/DC converter.

The system has four Caterpillar diesel generators, two rated at 160 kW and two rated at 60 kW. The larger units are configured for automatic operation and are capable of assuming station loads or battery charging duty without operator input. Since the electronic equipment is operated only sporadically, prior to the addition of the PV/battery hybrid the diesels ran for long periods at a small fraction of rated loads serving only the modest housekeeping loads. This resulted in cylinder glazing and increased maintenance costs (they have already been overhauled once). There was also increased incidence of diesel fuel spills. The addition of the RGS has markedly reduced diesel-run time, fuel requirements, and maintenance. During our visit, only the larger "automatic" units were in a ready-for-service mode.

The inverter for the DC output from the battery or PV array was fabricated by Advanced Energy Systems (AES) and is rated at 100 kW. The direct current (DC) is converted to 120/208-V, 3-phase electrical service, which is then distributed throughout the installation.

The battery was installed in January 1995. It was expected that relatively deep discharges would occur on nearly a daily basis. At this rate of usage, some 360 deep cycles would occur each year and 5 or more years would elapse before the rated life of 2000 cycles would be reached. However, the IPC representative stated that there were recent indications of two battery cycles/day, thus potentially surpassing the 2000 cycle expected life in a shorter time period. These clues suggested that the batteries were at, or approaching, end of life.

Another indicator that end of life was iminent was the appearance of widespread positive-plate swelling. Deep cycling causes morphology changes in the porous active material of the positive electrode that, over time, results in plate swelling and lengthwise plate growth. The lengthwise growth initially expands into the open space between the bottom of the electrode and the cell casing. When the case bottom is contacted, continued growth pushes the electrodes and the associated positive terminal upward. Most cells at the Grasmere site showed nearly a quarter of an inch of positive post upward movement.*

Idaho Power has been aware for some time that weaknesses were becoming apparent in some cells. Accordingly, arrangements were made to acquire replacement cells to extend the life of the overall system. During the week before Sentech's site visit, 24 new cells in a 12×2 series/parallel arrangement were "patched" into the 120-cell battery, and the weakest of the 12 original cells were bypassed with jumper cables. The new cells are C&D type CP. They are not identical to the originals, but with two cells in parallel, they are larger in capacity and are presumed, therefore, to be "safe" for the task. The goal of the "patch" is to extend operation of the battery into the year 2000 when monthly contributions to fund battery replacement will have been increased to their required levels to purchase a new battery.

Storage System Performance Analysis

Analysis of the Grasmere battery storage system follows the pattern used by Sentech in prior analyses. Operational parameters important to the lead-acid battery were identified and the data examined to evaluate battery exposure or performance in relation to these parameters. For Grasmere, the parameters were addressed in two groups: (1) abuse checks, and (2) critical measures.

Abuse checks refer to those operational parameters that may be relatively benign in moderation but would prove harmful if allowed to persist. Elements exhibiting the potential for abuse in lead-acid cells include the following:

- High rate of discharge,
- Deep DOD,
- High rate of charge,
- Extended periods of self discharge, and
- Physical mistreatment.

Each of the above factors tends not to affect battery lifetime or capacity on a single occurrence or even on occasional occurrences. However, where extreme levels are sustained or repeated, damage to individual cells may result.

The analytical approach was to identify the worst-case example for each element and to assess the frequency of occurrence if the worst-case value is potentially harmful. The Grasmere data were examined to determine worst-case occurrences for each of the parameters listed, and the results are shown in Table 2-28.

The four-hour discharge rate could be repeated for each discharge without harmful effect. The 72% discharge is below the manufacturer's 80% recommended limit (the next deepest discharge was 53%). The seven-hour charge rate was found to be a momentary peak and did not persist for even a single charge cycle. Daily cycling nullified opportunities for self-discharge (and potential sulfation damage). No evidence was uncovered to suggest that physical abuse had occurred.

* The Hoppecke design for the seal between the positive terminal and the case resembles a sleeve that traverses upward with the post while retaining, due to its length, firm contact with the case. In the Gras-mere cells, the design was clearly effective in that, in the storage system's 120 cells, no evidence of electrolyte leakage or acid misting was evident despite plate swelling and seal movement.

Table 2-28. Grasmere Battery Parameters

Criterion	Value
Discharge rate (highest)	C/4
Discharge depth (deepest)	72%
Charge rate (highest)	C/7
Longest idle time	< 1 day
Physical abuse	none

The battery does not appear to have been damaged by any of the operating parameters addressed.

Several parameters are more critical to battery health and require evaluation on a continuing basis throughout a battery's operating lifetime. For lead-acid batteries, these are:

- SOC,
- Degree of overcharge, and
- Temperature of operation.

Lead-acid systems are vulnerable to electrode sulfation if subjected to extended periods of low states of charge. Consequently, assessment of the lead-acid BES SOC can provide vital clues regarding the probable lifetime and available capacity of an operating battery. Lead-acid systems also require overcharge if full charge is to be reached on each cycle. Failure to overcharge can result in the gradual decline in SOC and slow onset of sulfation. In addition, higher temperatures exacerbate electrode and grid corrosion and shorten cycle life and battery operating lifetime.

The analytic approach was to evaluate a battery's condition for each of these parameters on a continuing basis. For SOC and degree of overcharge, this requires algebraic manipulation of ampere-hour values. For temperature assessment, summation of operating hours at unfavorable levels is required.

Normally SOC is evaluated on a cycle-to-cycle basis. Initial evaluation of Grasmere data, where each current reversal begins with a new cycle, is shown in Figure 2-37. Figure 2-37 shows more than 2000 cycles, many of which appear to be rapid shifts from discharge to charge involving small percentages of battery capacity and occurring within a single day. Since one of the major purposes of the SOC analysis is to infer a time of exposure to low discharge states, Figure 2-37 may be misleading.

To gain a clearer understanding of actual SOC, several artificial constraints were imposed on the data before plotting a graph. Nearly all related to the definition of a cycle. The most realistic result was obtained by defining a cycle as a minimum of six hours of current flow in one direction before a current reversal occurred. Under this constraint, the graphic representation shown in Figure 2-38 resulted.

The Figure 2-38 representation is considered closer to the actual occurrence since it results in about 340 cycles, more in agreement with the approximately 420 days of the 14-month period under evaluation. The conclusion to be drawn from this data is that, in the recent three- to five-month period, the battery has spent considerable time at a partial SOC, much of it below 80%, and significant portions below 60%. If true, this is counter to expectations of the analysis team and undoubtedly a surprise to the BESS operators.

The analysts recognize that Figure 2-38, based on a six-hour continuous current flow, may not be the most precise representation of the storage system cycling during the 14-month analysis period. Other definitions of a cycle are possible. Nevertheless, the general trends evidenced in this figure regarding SOC are undoubtedly accurate.

Lead-acid cells require overcharge to achieve full SOC following each discharge. This varies with cell design and manufacturer but tends to fall between 4 and 10%. Accordingly, for each cycle shown in Figure 2-38, the algebraic sum of the charge and discharge ampere-hours was calculated, and the results are presented in Figure 2-39.

The data support the indications from Figure 2-37 in that adequate recharges were not occurring after numerous discharges. As in the SOC information, the undercharge is most pronounced during the most recent three- to six-month time period. However, it is also important to observe that throughout most of the 14-month period of analysis, required overcharges were not being provided.

A major cause of lead-acid life reduction is elevated temperature. While temperature specifications for the Hoppecke cells installed at Grasmere were not available at the time of this report, manufacturers of similar lead-acid cells have issued guidelines indicating 30% cycle life reduction for operation over 30°C and 50% reduction over 35° C. The Grasmere data system recorded cell temperatures at two locations in the battery string. The percentage of time – by month – that these sensors recorded temperatures in excess of 30°C and 35°C is shown in Figures 2-40 and 2-41 respectively.

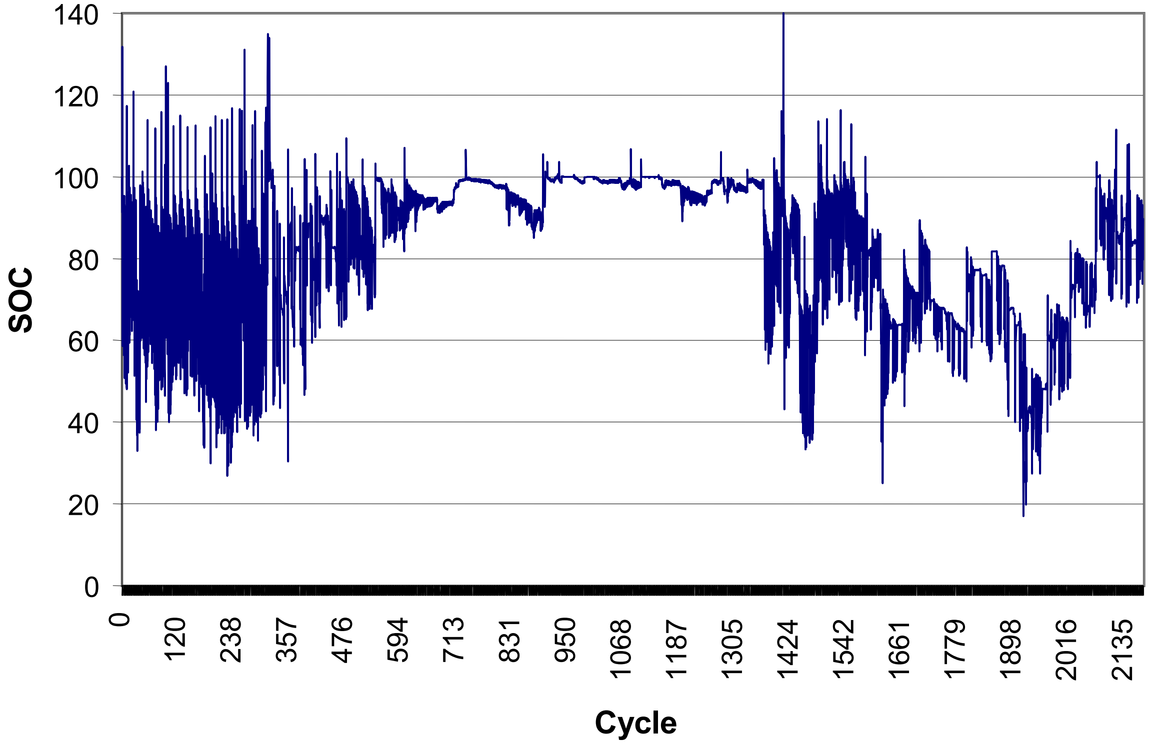


Figure 2-37. **Grasmere Battery SOC Based on Raw Data.**

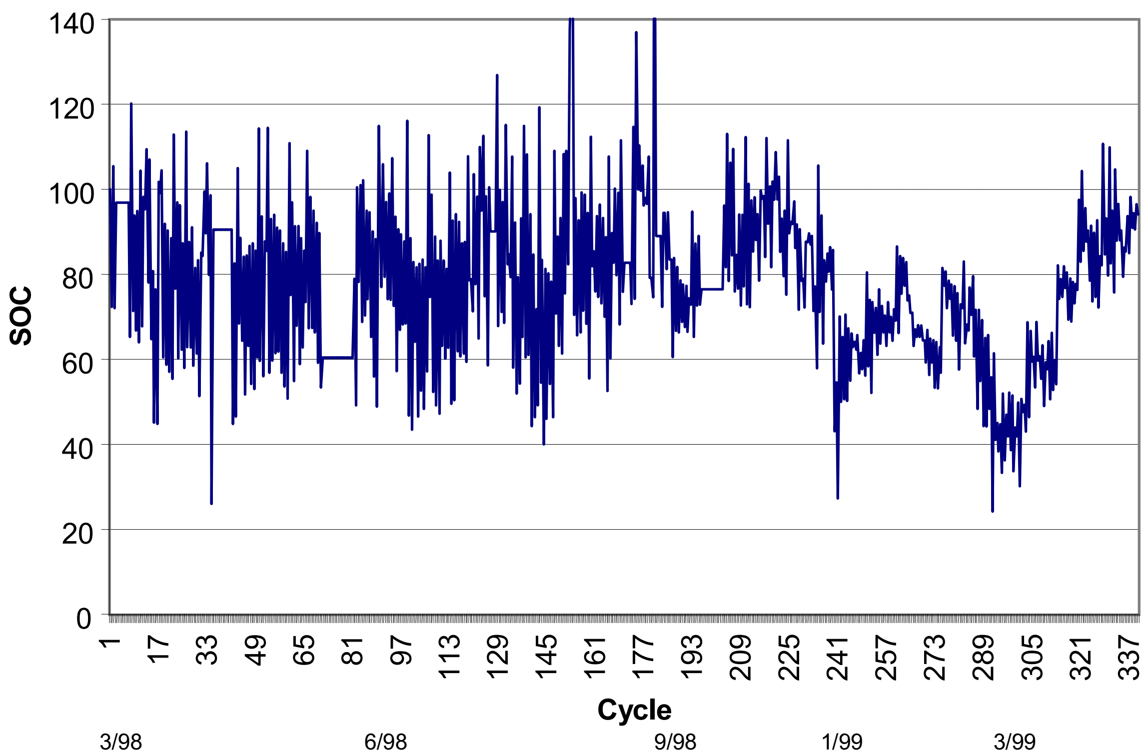


Figure 2-38. **Grasmere Battery SOC: Minimum Six Hours without Reversal.**

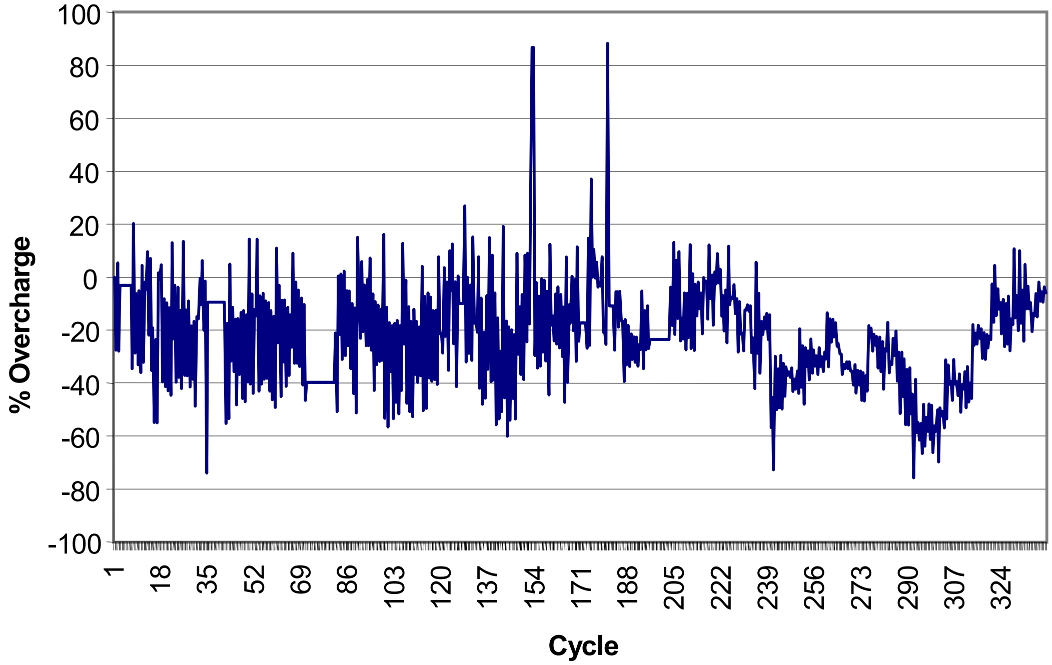


Figure 2-39. Grasmere Battery Degree of Overcharge and Undercharge.

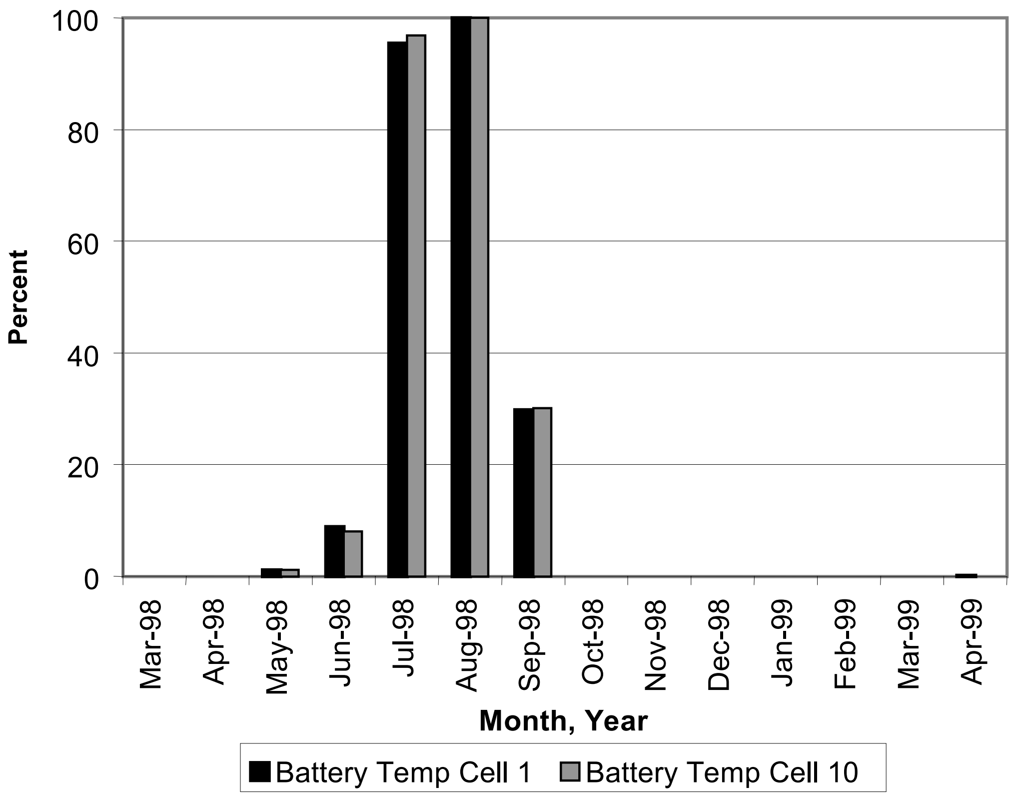


Figure 2-40. Grasmere Battery Operating Temperatures over 30°C.

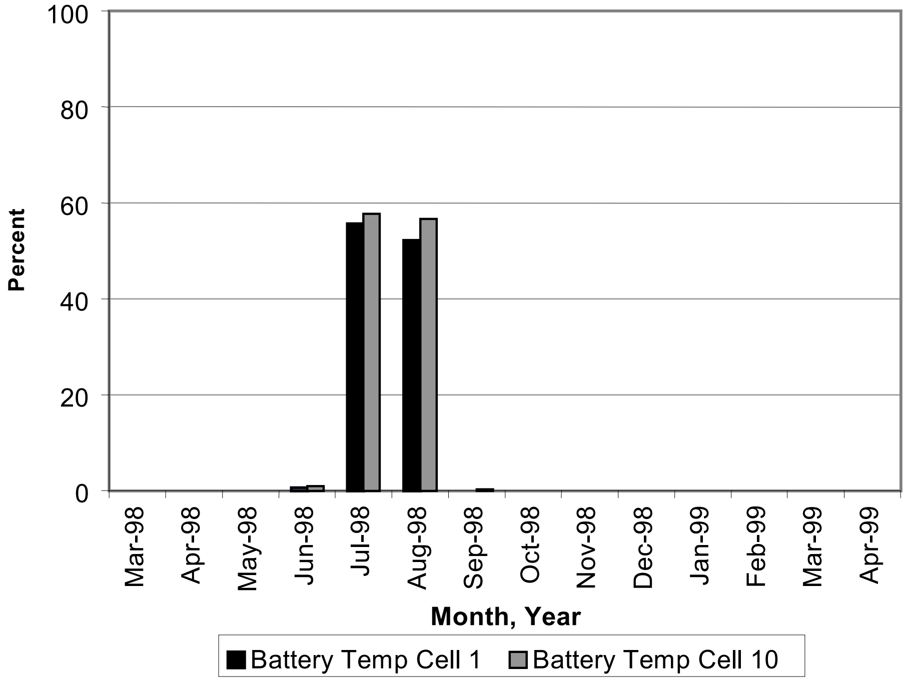


Figure 2-41. Grasmere Battery Operating Temperatures over 35°C.

The graphs indicate that temperatures are excessive during the summer months. In July and August, the 30°C level is exceeded virtually 100% of the time and the 35°C level is reached nearly 60% of the time. From an annual perspective, the total high temperature hours are in the 20% range, a factor that has undoubtedly affected battery life.

The previous analysis can be summarized to include favorable and unfavorable elements.

The favorable elements include:

- Mid-to-low-level of discharge, and
- Low-to-moderate charge and discharge rates.

The unfavorable elements include:

- Irregular SOC maintenance,
- Operation at elevated temperatures, and
- Insufficient overcharge.

It is Sentech's view that the unfavorable elements outlined above outweigh the favorable. This suggests that the Grasmere battery system is likely to provide somewhat less service than that suggested by the manufacturer for the duty cycle being experienced.

As indicated earlier, the Grasmere site is approximately 40 miles from the nearest electric network connection. The IPC representative estimated that the cost of grid extension would have been in the range of \$3 to \$5M. The actual RGS installation cost was approximately \$1.2M, of which \$250K was for the battery and \$330K for the PV system, \$140K for the inverter, and \$100K for the building. From IPC's viewpoint, the PV battery system was the lower capital cost option for providing electricity to the site.

PREPA System Lessons Learned

The 20-megawatt, 14-megawatt-hour BESS (Figure 2-42) was installed in June 1994 at the Sabana Llana substation near San Juan, Puerto Rico, primarily to mitigate under-frequency load shedding. The owner-operator, Puerto Rico Electric Power Authority (PREPA), and the architect/engineer and supplier firms learned many valuable lessons, from planning through the first four years of operations, about the largest "commercial" battery system in operation in an electric utility application. PREPA collaborated with the ESS Program to compile a "lessons learned" report for the facility. The report, *Lessons Learned from the Puerto Rico Battery Energy Storage System* in English and Spanish versions (SAND99-2232), was published in September 1999.

Since it first began operations in 1994, the BESS has responded to dozens of load shedding events and

Figure 2-42. Battery Storage Building in Puerto Rico.

continuous demand for frequency regulation. Almost every key component experienced some problem during initial start-up and operations. PREPA and their vendors and contractors have solved many of these problems. Still, other challenges remain. Despite these problems, however, the BESS performed admirably in the aftermath of the worst hurricane to hit the island this century (Hurricane Georges in October 1998). The plant was able to maintain voltage support on the only transmission line from San Juan to the northeastern region that was still operating after the hurricane.

Status

The ESS supports PREPA generation operations with rapid reserve and frequency control, T&D with voltage regulation, and customers with more reliable service.

The lessons learned report was published in September 1999 in both English and Spanish. The following is a summary of that report:

- Spinning reserve (SR) is defined as the unused generation capacity that is synchronized to the network and can respond within ten minutes to prevent interruption of service to customers (load shedding) in the event of a failure of an operating power plant.

- Rapid reserve is a portion of SR that is available almost instantaneously to prevent automatic load shedding.

- Frequency control is the regulation of frequency of the electricity that utilities produce within a narrow band around 60 Hz (standard in the U.S.).

- Voltage regulation is the ability of a power source to maintain constant output voltage with changes in load.

PREPA designed its BESS to function primarily in the rapid reserve mode, preventing load shedding in its island network. The BESS experienced its first rapid discharge on November 23, 1994. A 410-MW unit of PREPA's South Coast Steam Plant was lost, resulting in a 21% system overload. Load shedding was necessary, but the magnitude of the event was reduced because of the availability of the BESS.

PREPA's experience identified many pitfalls as well as optimum processes for planning, design, procurement, construction, operation, and maintenance of a large, integrated energy storage facility. The lessons learned document will be useful to the other utilities considering construction of similar facilities. The lessons learned are presented by project phase (see Figure 2-43) to indicate the type of challenges that can arise during each phase of a project.

This project was initiated in 1989, with internal planning documents prepared by the PREPA Planning Division with assistance from its architect/engineer, United Engineers & Constructors (UE&C). The utility evaluated alternative technologies, including batteries, flywheels, and gas turbines to combat frequency control

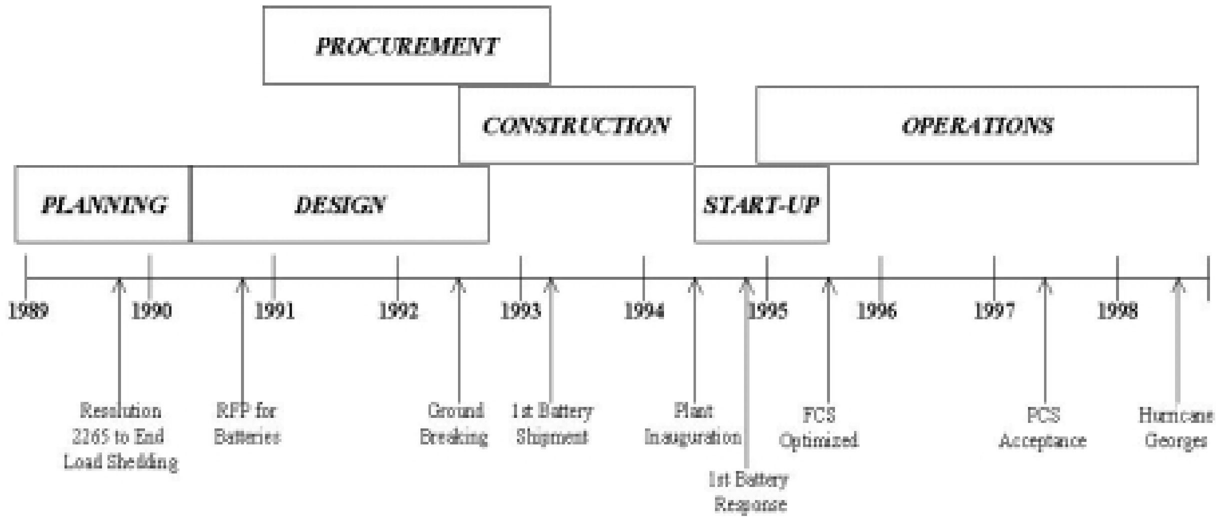


Figure 2-43. Project Timeline and Key Milestones.

issues that caused load shedding. PREPA was able to draw upon the experience of two large BESS facilities already in operation: Southern California Edison's (SCE's) 10-MW/4-hour Chino facility operating since 1988 and Berliner Kraft und Licht's (BEWAG's) 17-MW/30-minute battery plant operating since 1987. PREPA determined that a BESS would provide the quickest response to power fluctuations and achieve the fastest payback. During the planning phase, the following lessons were learned:

- Establish a team to follow the project through to completion.
- Identify up front who is responsible for the system within the organization throughout all project phases.
- Determine project responsibilities for all participants before going to procurement.
- Coordinate meetings with licensing boards to facilitate the permitting process.
- Gather and evaluate as much performance data on other facilities as possible.

The PREPA staff had considerable communications with UE&C, who directed the design/engineering phase. The utility wanted to make certain that the BESS was not a first-of-a-kind demonstration like the Chino and BEWAG plants. They insisted that all subsystems consist of commercially available components. However, very few components were in fact purchased off the shelf. In addition, PREPA did not want a turnkey project in which they would have minimal involvement; the utility wanted to be the system integrator. These two conditions significantly impacted the design/engineering phase. PREPA learned that the system integrator must:

- Select the architect/engineer with the most relevant experience.
- Be an active participant in system design.
- Accept that project phases are intertwined in large competitive solicitations (e.g., design phase overlapping procurement and construction phases).
- Verify available infrastructure before preparing an appropriate design (e.g., roads and the supply of electricity and water).
- Identify and design for site-specific environmental and climatic conditions.
- Design the building to facilitate regular maintenance and major overhauls.
- Consider the performance and cost implications of subsystem design and configuration.

PREPA coordinated the procurement processes. Having a public power authority control procurement extended a complicated process, with seven sequential solicitations, into a two-year effort. In addition, PREPA had not built a major facility for 15 years.

Nonetheless, PREPA staff undertook a number of initiatives that paved the way for construction:

- Dedicated a purchaser in the organization to ensure good communications and project continuity.
- Budgeted for cost variations (see Table 2-29).
- Ensured that all potential bidders are invited.
- Designed specifications that avoid multiple interpretations.
- Developed contingency plans for off-schedule equipment deliveries.

During the construction phase, PREPA worked closely with the general contractor, who had ample experience in the construction of reinforced concrete buildings. However, the contractor's lack of experience with electric power installations prolonged the construction period even though PREPA O&M personnel were present throughout construction. The participation of key team members enabled several beneficial changes to building design during construction. Nonetheless, more proactive participation by the battery vendor and architect/engineer would have facilitated construction and acceptance testing.

- Bring all suppliers together to review system impacts of subsystem designs.
- Build time into the schedule for weather-related delays and construction errors.
- Ensure that general contractors use qualified subcontractors for specialized work.

After inauguration of the BESS in July 1994, PREPA experienced a frustrating start-up period. The system failed frequently, and it took months for the team to pinpoint all the causes of failure (such as corrosion on the gold-plated pins of the PCS). Likewise, domino effects further complicated the isolation of problems in component design and operation. PREPA staff were able to resolve these initial start-up problems because of their involvement in all phases of the project. The major lessons learned in this phase were to:

- Verify control software for battery management (original charging algorithm did not result in full state-of-charge).
- Monitor all systems for unanticipated problems.
- Install appropriate ground detection equipment.
- Interface the BESS with central utility dispatch operations.
- Access design and construction staff as needed to resolve start-up issues.
- Allow for a long start-up period for one-of-a-kind projects.

Table 2-29. PREPA BESS Costs by Components ($M)

Contractor	Principal Components	Proposed Bid	Ultimate Cost
United Engineers & Constructors	Design/Engineering	0.95	1.49
C&D Charter Power	Batteries, Racks, Watering System	4.60	4.84
General Electric	PCS	5.40	5.40
Pauwels	Transformers & 115 kV Interface	0.36	0.70
ABB	AC Switchgear	0.19	0.19
PACS Industries	DC Switchgear	0.50	0.72
Leeds & Northrup/ Applied Control Systems	Facility Control System & Monitoring	0.80	1.33
Aireko	Construction & Balance of Plant	4.00	4.85
PREPA	Project Mgmt, Training, Testing	----	0.80
TOTAL		**16.80**	**20.32**

Continuity in PREPA's BESS team facilitated the transition from initial start-up to full operations. One team member, who had been involved with the facility since the construction phase, continued as the plant manager through 1997. Unique problems in system operations were solved during the first two years of operation. PREPA staff made many modifications that improved BESS performance (a typical BESS rapid reserve response on May 2, 1997, is shown in Figure 2-44). Areas of concern and lessons learned in this phase include:

- Coordinate smooth turnovers with all participants.
- Maintain trend data on BESS responsiveness.
- Improve operations by addressing engineering details.
- Choose upgradable, nonproprietary electronics and data systems.
- Implement fully debugged data tracking.
- Identify root cause of excessive cell failure.

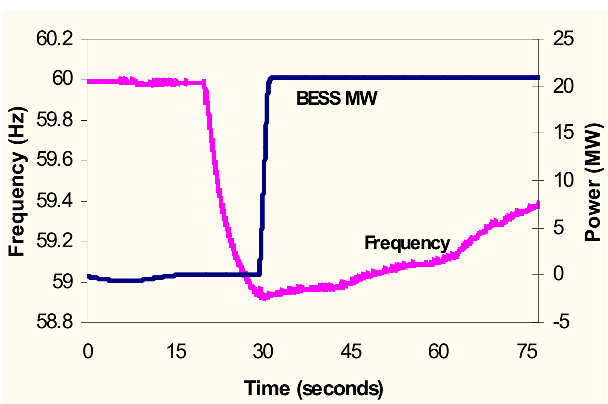


Figure 2-44. BESS Rapid Reserve Response on May 2, 1997.

Battery cell failures and replacement have been the biggest maintenance issues. Building logistics aggravate this situation (rack design, no elevator to the second floor, and limited heavy equipment handling capability). The smallest BESS outage possible to replace a few localized cells is one-third of one floor (one string is comprised of three rows). Typically, an entire floor must be taken out of service, leaving only 10 MW available for load shedding avoidance. The time and effort required to change out cells is significant and costly. Three men can remove and replace a maximum of 16 cells in a day. The entire battery contains 6000 cells. Figures 2-45 through 2-47 show one part of the removal and replacement effort. One of the biggest problems is rack design, which provides no clearance between the rack and the cell jars to permit the use of a forklift. The BESS battery technician designed a sling that was used successfully to remove good cells. A V-shaped forklift was also designed to permit removal of good cells from the bottom rack. The primary lesson learned here was to design the system for ease of maintenance:

- Acquire tools appropriate for maintenance.
- Install equipment to facilitate maintenance and safeguard personnel.
- Have realistic staffing expectations.
- Establish appropriate warranty conditions.

The BESS is contributing in a way no other generation asset can. The facility has successfully achieved its goal of providing rapid SR, frequency control, and/or voltage regulation. This was particularly the case in the aftermath of Hurricane Georges in 1998. Rapid discharge from the BESS continues to provide a reduction in network load shedding and in required system-wide SR that result in economic benefits for the utility. In frequency regulation mode, the BESS provides a fast response that reduces frequency deviations and provides operational flexibility during generation shortages. The BESS in voltage regulation mode helps sustain system voltage levels, especially during peak hours, by augmenting the reactive power load. PREPA is in the process of deciding how to proceed with cell replacements, and is determined to improve state-of-charge measurement and data acquisition flaws that hampered operations. The utility is now beginning the process of reviewing cell specifications for a second BESS facility located at the same substation near San Juan.

Despite the best efforts of those involved in the project, the PREPA BESS was still a first-of-a-kind system with its share of unanticipated problems. The lessons learned from this project should help future large BESS projects achieve full operational status in a minimum amount of time.

Figure 2-45. Disconnecting Cells.

Figure 2-46. Removing Failed Cell.

Figure 2-47. Installing Good Cell.

Peru System Field Test Monitoring

In July 1997, the International Lead-Zinc Organization (ILZRO), the ESA, the Solar Energy Industries Association, and the country of Peru signed a memorandum of understanding (MOU) for a collaborative project. The objective of the first phase of the project was to perform a feasibility study for photovoltaics in combination with storage, power electronics, and controls for use in remote villages in the Amazon River valley.

The feasibility study included a discussion of system and component sizing, performance benefits, and economic benefits. The cost of the study was shared by the MOU signatories and the ESS Program. Results of the approximately six-month study are documented in an ILZRO report. The MOU signatories have now started the hardware demonstration phase. ESS-funded activities in FY99 were planned for providing DASs in up to four demonstrations once system hardware was purchased.

Status

Several meetings were held with ILZRO to discuss the status of their hardware demonstration. Activities focused on identifying funding sources for the hardware. The potential funding sources were approached, but no funding was secured in FY99. No further action will be taken on the DAS until the funding sources for the demonstration have been finalized.

PV/Battery Hybrid Controller Field Test

The initial evaluation of the first PV/battery hybrid controller at the SNL PV System Evaluation Laboratory (PSEL) was completed in FY95. A project plan was developed that called for the installation of the second prototype control unit at a site that could provide at least a 15-kW PV array, a 200-kWh battery, 30-kW genset, and a variable load that would simulate the electric power consumption of a small village. A multiyear operational test plan was successfully negotiated with APS to perform a complete system field test of the controller at the APS STAR Center in Tempe, Arizona. An MOU and a loan agreement were finalized in FY97. The MOU provided for the loan of a state-of-the-art inverter/controller and a DAS for up to three years. APS acquired a tubular gel VRLA battery through a special agreement with Yuasa, Inc., to expand the test results to determine whether the gel technology battery was best suited for the hybrid operational environment. A special hybrid test facility was constructed at STAR to house the battery, inverter/controller, and natural gas genset. The STAR Center with nominal loads of 2 to 35 kW would provide the desired loads for the test program. Two multiyear contracts were placed in FY98 to provide operation and maintenance for the DAS and in-depth analytical support for data generated by the system. Results from the analysis of the operational data generated at STAR are expected to provide better understanding of how to manage the components in the off-grid hybrid system operational environment.

Status

The Trace 30-kW inverter remained idle throughout the first quarter as APS continued a high priority test program on another inverter. Prior to placing the 30-kW inverter in mothballs in early October 1998, the Yuasa DGX battery was fully charged and placed on open circuit. The inverter was placed back in service in January 1999.

Three meetings were held during the second quarter. The first and second, held at SNL and at STAR, respectively, had as their primary purpose an evaluation of the status of the Yuasa cells at STAR. The third meeting, held at Yuasa's offices in Reading PA, was needed to discuss the results of the STAR and Yuasa lab testing and to then determine future courses of action. The results of the analyses performed by EECI were used as presentation materials at these meetings. Selected graphics from these presentations will be included in the final report for the present phase of the work.

The most important conclusions that resulted from the analyses and from the meetings were:

- The STAR battery with the Yuasa gel cells is performing quite well in the solar hybrid system, although the depth to which the battery is discharged is somewhat deeper than ultimately desirable.

- Capacity testing of the Yuasa gel VRLA battery at STAR revealed that there were two cells, one in each string, that had a capacity that was ~30% less than rated. These two weak cells determine the capacity of the entire battery because of the way this test was managed. Yuasa initiated the process of obtaining some replacement cells for the weakest ones in the STAR battery.

- Since the batteries in solar hybrid systems will be cycled only to ~50% DOD, continued operation with the two weak cells should not be too problematic.

- The test procedures being used for Yuasa testing at SNL appear acceptable. The data show that the capacity returned during a battery charge is slightly greater than that removed in a battery discharge, but is probably insufficient to make up for coulombic inefficiencies in battery cycling.

- The apparent loss of capacity of the gel VRLA battery at SNL has been traced to the one very weak cell. It was concluded that this cell should be removed from test, and that cycling should then be resumed. The data from the battery cycling should again be reviewed after the next charge cycle has been completed.

- In future Yuasa lab testing, consideration should be given to performing full equalization charges before conducting capacity tests.

The STAR hybrid facility was inactive during the first half of April while the 30-kW Trace inverter underwent extensive upgrades. During this period, Cell No. 68 in Bank A was replaced with a spare cell that had been at open circuit for 18 months (identified as Cell 68-S, S for spare). Cell 68-S was equalized at 2.35 Vdc for 80 hours from April 5 through 8, 1999, and it recovered to full capacity as indicated by the manual cell voltage readings of April 26 (Table 2-30). A significant conclusion is that the Yuasa Dynacel DGX85-11 can survive 18 months at open circuit and be restored to full capacity by standard equalization. Data show that it is desirable to equalize a battery that sits on the shelf for 18 months before it is placed in service.

The hybrid test did not resume normal operation until May 6, 1999, when a capacity test was performed (see Figures 2-48 and 2-49). The results of this test showed that the battery bank could only deliver 58% of rated capacity (495-Ah actual vs. 850-Ah rated). Two weak cells that were rapidly approaching cell reversal (Pilot Cells [PC] No. 2 and No. 4) primarily caused the poor performance. The capacity test was terminated to prevent cell reversal (rather than allow the battery bank to discharge to 210 V, i.e., 1.75 Vpc average), which

Table 2-30. Comparison of Yuasa Battery Manual Cell Readings: April to June 1999

6/23/99						5/26/99						4/26/99					
Bank A (East)			Bank B (West)			Bank A (East)			Bank B (West)			Bank A (East)			Bank B (West)		
	PC			PC			PC			PC			PC			PC	
Cell 73	1	2.209	Cell 28		2.208	Cell 73	1	2.205	Cell 28		2.204	Cell 73	1	2.135	Cell 28		2.126
Cell 98		2.205	Cell 45		2.207	Cell 98		2.200	Cell 45		2.202	Cell 23		2.128	Cell 56	3	2.126
Cell 13		2.203	Cell 75		2.206	Cell 13		2.198	Cell 75		2.201	Cell 98		2.128	Cell 64		2.126
Cell 23		2.203	Cell 76		2.206	Cell 23		2.198	Cell 76		2.201	Cell 13		2.127	Cell 75		2.126
Cell 33		2.201	Cell 59		2.204	Cell 65		2.197	Cell 48		2.200	Cell 8		2.124	Cell 76		2.126
Cell 65		2.201	Cell 64		2.204	Cell 33		2.196	Cell 64		2.200	Cell 33		2.124	Cell 45		2.124
Cell 103		2.201	Cell 48		2.203	Cell 55		2.196	Cell 56	3	2.199	Cell 65		2.124	Cell 59		2.123
Cell 8		2.199	Cell 56	3	2.202	Cell 56		2.196	Cell 59		2.199	Cell 28		2.123	Cell 54		2.122
Cell 56		2.199	Cell 57		2.202	Cell 57		2.196	Cell 57		2.197	Cell 78		2.123	Cell 55		2.122
Cell 57		2.199	Cell 7		2.201	Cell 68		2.196	Cell 106		2.197	Cell 25		2.122	Cell 57		2.122
Cell 78		2.199	Cell 106		2.201	Cell 103		2.196	Cell 7		2.196	Cell 43		2.122	Cell 96		2.121
Cell 105		2.199	Cell 54		2.200	Cell 105		2.195	Cell 54		2.195	Cell 48		2.122	Cell 106		2.121
Cell 18		2.198	Cell 66		2.200	Cell 5		2.194	Cell 66		2.195	Cell 68		2.122	Cell 7		2.12
Cell 28		2.198	Cell 81		2.200	Cell 8		2.194	Cell 81		2.194	Cell 103		2.122	Cell 81		2.12
Cell 46		2.198	Cell 3		2.198	Cell 28		2.194	Cell 96		2.194	Cell 18		2.121	Cell 69		2.119
Cell 74		2.186	Cell 34		2.186	Cell 102		2.183	Cell 100		2.183	Cell 92		2.11	Cell 87		2.108
Cell 99		2.186	Cell 58		2.186	Cell 2		2.182	Cell 29		2.182	Cell 104		2.11	Cell 98		2.108
Cell 114		2.186	Cell 61		2.186	Cell 4		2.181	Cell 49		2.182	Cell 67		2.109	Cell 109		2.108
Cell 4		2.185	Cell 17		2.185	Cell 20		2.181	Cell 63		2.182	Cell 84		2.109	Cell 58		2.107
Cell 37		2.185	Cell 26		2.185	Cell 37		2.181	Cell 87		2.182	Cell 11		2.108	Cell 5		2.106
Cell 102		2.185	Cell 63		2.185	Cell 47		2.181	Cell 26		2.181	Cell 64		2.108	Cell 26		2.106
Cell 2		2.184	Cell 77		2.185	Cell 81		2.181	Cell 77		2.181	Cell 99		2.108	Cell 29		2.106
Cell 10		2.184	Cell 99		2.185	Cell 114		2.181	Cell 17		2.180	Cell 108		2.108	Cell 35		2.106
Cell 14		2.184	Cell 22		2.184	Cell 10		2.18	Cell 22		2.180	Cell 34		2.107	Cell 99		2.106
Cell 108		2.184	Cell 49		2.184	Cell 108		2.180	Cell 94		2.180	Cell 44		2.107	Cell 115		2.106

Note: PC = Pilot Cell

Table 2-30. Comparison of Yuasa Battery Manual Cell Readings: April to June 1999 (Continued)

6/23/99						5/26/99						4/26/99					
Bank A (East)			Bank B (West)			Bank A (East)			Bank B (West)			Bank A (East)			Bank B (West)		
	PC			PC			PC			PC			PC			PC	
Cell 42		2.183	Cell 94		2.183	Cell 14		2.179	Cell 98		2.180	Cell 47		2.107	Cell 17		2.105
Cell 81		2.183	Cell 109		2.183	Cell 52		2.177	Cell 35		2.179	Cell 37		2.106	Cell 92		2.104
Cell 59		2.181	Cell 35		2.182	Cell 11		2.176	Cell 99		2.179	Cell 114		2.106	Cell 102		2.104
Cell 11		2.179	Cell 98		2.182	Cell 42		2.173	Cell 109		2.179	Cell 42		2.102	Cell 49		2.103
Cell 52		2.179	Cell 102		2.182	Cell 59		2.170	Cell 102		2.176	Cell 59	2	2.102	Cell 22		2.102
Cell 9		2.178	Cell 43		2.176	Cell 9		2.168	Cell 43		2.173	Cell 12		2.1	Cell 43		2.102
Cell 12		2.178	Cell 112		2.170	Cell 12		2.167	Cell 103		2.164	Cell 9		2.099	Cell 103		2.098
Cell 39		2.173	Cell 103		2.166	Cell 39		2.162	Cell 112		2.162	Cell 39		2.097	Cell 112		2.094
Cell 49	2	2.156	Cell 108	4	2.155	Cell 49	2	2.151	Cell 108	4	2.147	Cell 49		2.097	Cell 108	4	2.089

Note: PC = Pilot Cell

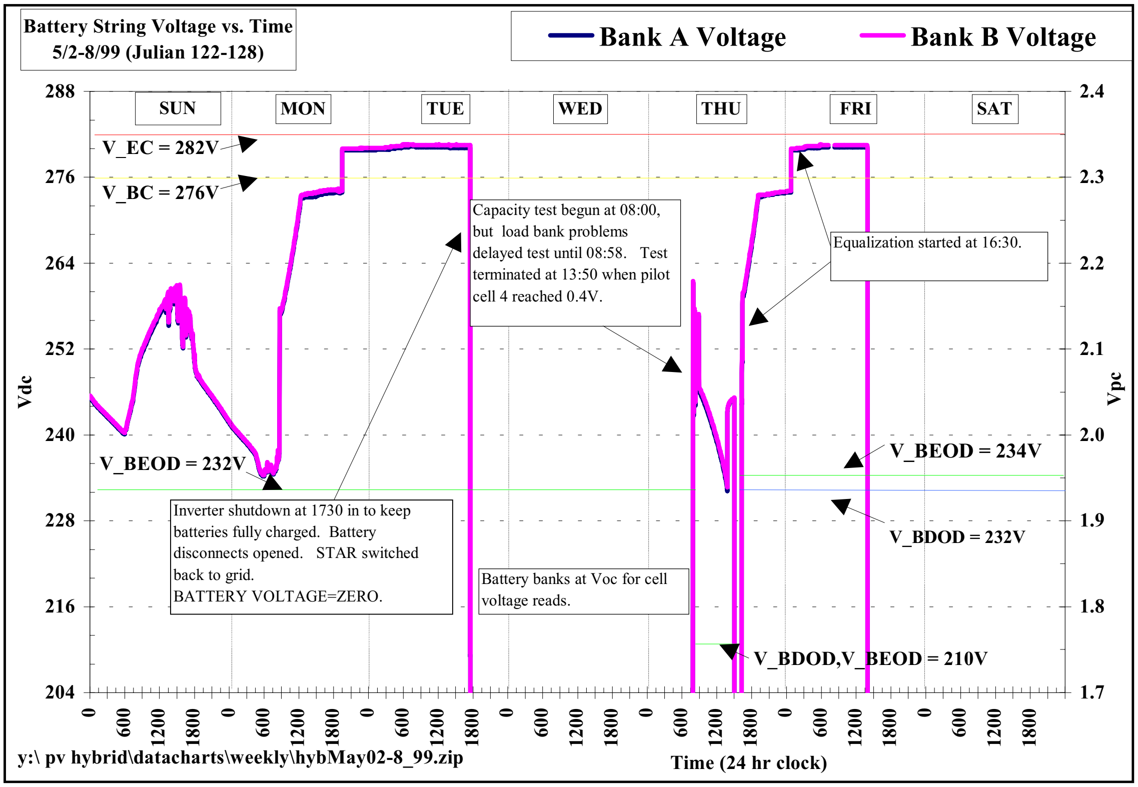


Figure 2-48. Battery String Voltage vs. Time, May 2 through 8, 1999 (Julian 122-128).

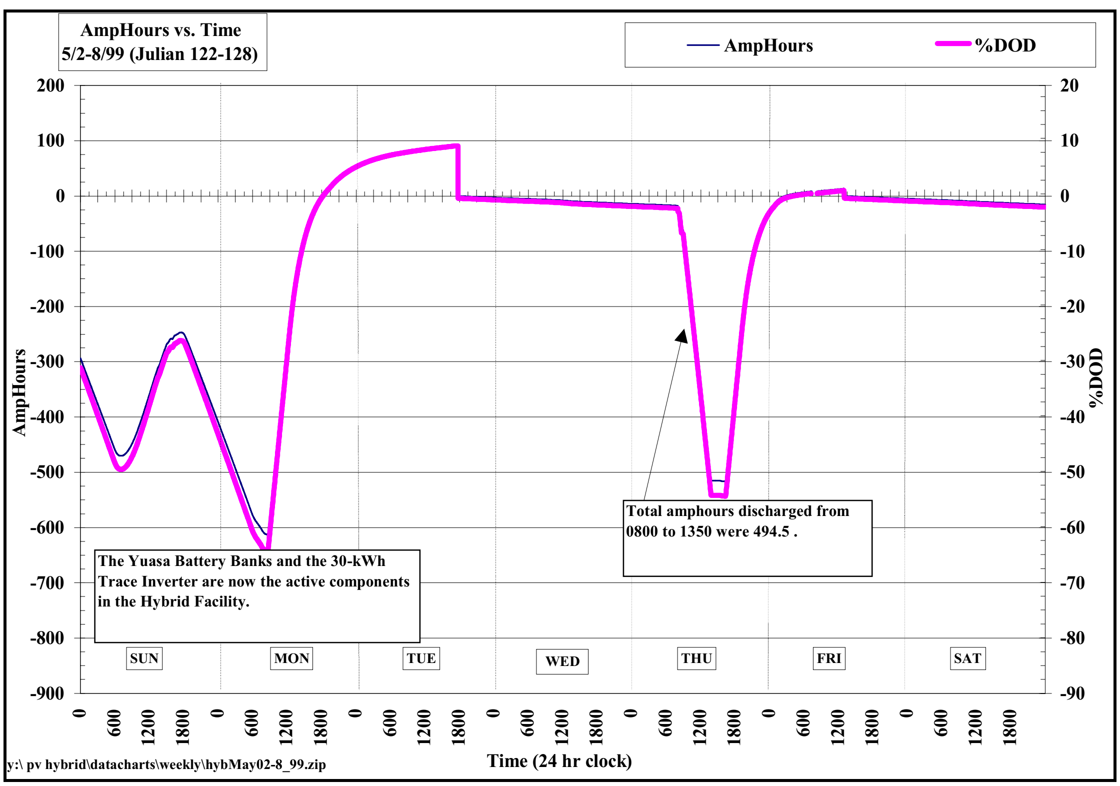


Figure 2-49. Battery String Amp-hours and % DOD vs. Time, May 2 through 8, 1999 (Julian 122-128).

limited the capacity of the entire bank to the weakest cell. Had these two cells been allowed to experience voltage reversal, the actual capacity would have been significantly higher. PC No. 4 recovered to 1.99 Vdc after being at open circuit for 1.5 hours.

Normal operations continued until May 17, at which time the 30-kW Kohler generator began experiencing over-speed fault conditions (it could not provide the STAR Center air conditioning starting current). Operation began again on June 7, when the maximum generator-power set point for the inverter was modified from 30 kW to 25 kW and the factory-modified inverter power "signal conditioner" was reinstalled. Further difficulties with the generator created the need for more modifications to this set point during June. A summary of inverter set points is shown in Table 2-31. A preliminary conclusion drawn from these generator difficulties is that it is undersized for this application. A 90-kW generator is currently awaiting connection. There was also suspicion that the inverter was not functioning properly and may be a cause for the generator fault.

By the end of the fourth quarter of FY99, after 26 months of service at the STAR Center, the consensus is that the Yuasa DGX85-11 VRLA-gelled electrolyte batteries have performed well. Capacity tests have been performed periodically to measure overall performance as shown in Table 2-32. As was noted earlier, measured battery capacity decreased during the period of September 10, 1998 to May 6, 1999, due to several weak cells. A few weeks prior to a capacity test in early August, the five weakest cells were replaced with five new cells. During the capacity test (two 120-cell parallel strings–Banks A and B), it became apparent that Bank A was reaching end of charge faster than Bank B due to two weak cells in Bank A. Bank A's discharge was terminated when the two weak cells approached reversal (Bank A measured capacity = 293 Ah; 69% of rated capacity). Bank B was discharged until the average cell voltage was 1.75 Vdc (measured capacity = 441 Ah; 104% of rated capacity), and no cell approached reversal. The total capacity of the two banks was 733 Ah; 86% of rated capacity.

Data show that the weakest cell in the string limits the actual capacity of a string of batteries. If the weakest cell becomes reversed biased, it also creates a safety hazard, since the reverse-biased cell can become very hot. Culling out weak cells is an effective method to maximize the capacity of a string of batteries.

Data Analysis from PV/Hybrid Controller Testing

Following a competitive bidding process, which began late in the first quarter of FY99, a contract for analytical support was awarded in early February to EECI of Morgan Hill, California. EECI was given the task of providing analyses of data collected at the APS STAR Center for the Hybrid Controller Field Test Program.

The overall objective of the DOE/SNL project at STAR is to develop an operational strategy for solar hybrid systems, which includes energy storage that will maximize performance and minimize the life cycle cost of these systems.

The secondary objectives for the data analysis that is under way at EECI are as follows:

1. Assist SNL and APS personnel in fine-tuning the Trace controller so that the electric loads are supplied reliably and efficiently.

2. Ensure that the Yuasa cells in the energy storage battery at STAR are being maintained, repaired, and operated in a way that will maximize life and performance.

3. Make a preliminary determination of the usefulness of gel VRLAs in the solar hybrid application.

The solar hybrid test facility at STAR (Figure 2-50 shows a block diagram) consists of the following:

- A 20-kW (approximately) PV array;

- A 30-kW gas-fired engine-generator;

- A 200-kWh battery with two strings each with 120 Yuasa DGX gel VRLA cells; and

- A 30-kW PCS together with a controller to dispatch the other components as necessitated by the battery SOC, the load, and the availability of solar power.

The PCS was loaned to the project by SNL. A DAS based on a Campbell Scientific CR9000 hardware and software package was also loaned to the project by SNL. The DAS allows measurement and recording of many parameters, including:

- Meteorological data and temperatures in the battery and the converter room;

Table 2-31. STAR Hybrid Test Facility 30-kW Trace Inverter Set Point Log

SET POINT NAME	NOTES	UNITS	As of 09:15am 6/14/99		As of 12:00pm 6/28/99		As of 7:00am 6/30/99	
			Value	VPC	Value	VPC	Value	VPC
Goal State		n/a						
Max AC Volt		V	226	1.883	226	1.883	226	1.883
Min AC Volt		V	185	1.542	185	1.542	185	1.542
Max AC freq		Hz	62		62		62	
Min AC freq		Hz	58		58		58	
Max AC delay		s	5		5		5	
Min AC delay		s	5		5		5	
Max Freq delay		s	5		5		5	
Min Freq delay		s	5		5		5	
Max Gnd Fault I		A	10		10		10	
V_EC	EC = Equalization Charge	V	282	2.350	282	2.350	282	2.350
I_EC		A	100		100		100	
T_BE	BE=Battery Equalization	min	900		900		900	
T_Between Equ	Time Interval Between Equalizations	hr	168		168		168	
V_BC	BC=Battery Charge	V	276	2.300	276	2.300	276	2.300
I_BC		A	100		100		100	
I_CCO	CCO=Charge Cut-Out	A	10		10		10	
V_BEOD	BEOD=Battery End of Discharge	V	234	1.950	234	1.950	234	1.950
V_BDOD	BDOD=Battery Depth of Discharge	V	228	1.900	228	1.900	228	1.900
Bat_Volt_Comp		1=-1mv/A	0		0		0	
Bat_Temp_Cmp		1=.01V/degC	0		0		0	
PV Start Voltage		V	300	2.500	300	2.500	300	2.500
PV Stop Power		kW	1		1		1	
PV Start Delay		min	1		1		1	
PV Stop Delay		min	6		6		6	
Gen Warm Time		s	60		60		60	
Gen Max Power		kW	25		20		15	
Gen Enable	24hr Clock	n/a	3:00		3:00		3:00	
Gen Disable*	24hr Clock	n/a	7:00		7:00		7:00	
Pwr Track Rate		Hz	1		1		1	
Pwr Track Istep		A	1		1		1	
Gen Fail Delay		s	60		60		60	
Var Current		A	-15		-15		-15	
Min Vbat Tcomp		V	200	1.667	200	1.667	200	1.667
Max Vbat Tcomp		V	300	2.500	300	2.500	300	2.500
BAT DI Current		A	4		4		4	
Date		n/a						
Time		n/a						

*This value needs to be revised during the winter months as the time for su nrise becomes later in the day.

Table 2-32. STAR Yuasa Battery Bank Capacity Test Comparison

Parameter	9/10/98 Test	10/7/98 Test	5/6/99 Test	8/5/99 Test
Amp-hour capacity	607	575	495	733
Percent of rated capacity	71.00%	68.00%	58.00%	86.00%
Load power (kW)	25	25	20	25
Average battery current (Adc)	66.3	55.3	42.42	51.67
Test duration (hrs)	4.60	5.25	5.87	7.82
Min battery voltage (Vdc)	214.6	226.6	232.70	206.10
Min battery voltage (Vpc)	1.79	1.89	1.94	1.72
Min Pilot Cell #3 (V)	1.84	1.93	1.97	1.83
Min Pilot Cell #4 (V)	1.84	0.13	0.50	1.79

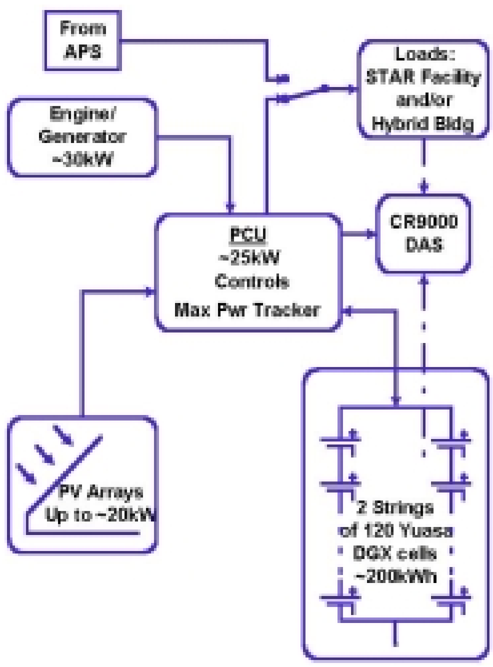


Figure 2-50. Block Diagram of STAR Solar Hybrid Facility.

- AC and DC currents to and from the PCS;
- Real and reactive power flows between and among the components and the load;
- String voltages and currents;
- Voltage of each group of 12 cells. The 12-cell groups are called modules although there is no physical packaging that identifies a group as a module;
- Temperature of 20 of the cells in the battery, one in each of the modules; and
- Voltages of four pilot cells.

These data are collected, averaged over a two-minute period, and saved on a PC hard drive that is permanently attached to the solar hybrid system. The data are collated and graphed by personnel from Arizona State University (ASU) under a separate contract between SNL and ASU. The collated data are then sent to EECI for further analysis on a daily and/or weekly basis; more detailed data are sent when the analyses indicates that more data are r equired.

Status

The work performed by EECI, beginning on February 4, 1999, has met all three of the secondary objectives for this Data Analysis Project. For the first two secondary objectives, this progress is indicated by the results from the testing of the solar hybrid system at STAR. The results of work toward the third secondary objective will not be apparent until much more testing has been performed, and will therefore not be addressed in the this report.

Progress toward the first secondary objective, fine-tuning the Trace controller for reliable and efficient operation, is best exemplified with the results shown in Figure 2-51.

Figure 2-51 also shows the power flowing among the various components of the solar hybrid system for two days in August 1999. The power flowing to the load, which at the time was the STAR facility itself, is not shown in Figure 2-51, for the sake of clarity. The power to the load is the same as the inverter power when the generator is not running, and is the difference between the generator power and the inverter power when the generator is running. During a summer day, the average power to run the STAR facility is approximately 16 kW, with somewhat lower levels at night.

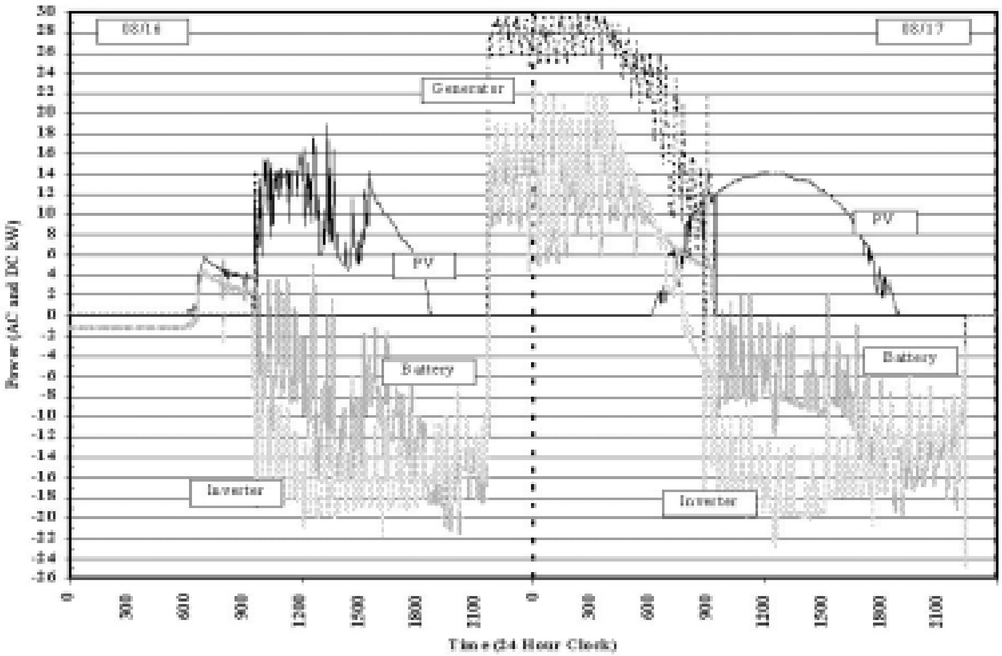


Figure 2-51. Power Flows for Components in STAR Hybrid Tests.

The wide variation in each of the power levels, except for what was generated by the PV arrays, is due to large loads (primarily air conditioning units) switching on and off. The loads during August are among the highest of the entire year for the Phoenix area where the STAR facility is located.

Figure 2-51 does not show the full variation of the loads that occur, since the data are averaged over two-minute periods. Peak loads of more that 35 kW for a few 60-Hz cycles, and of 25 kW for up to a minute, must frequently be supplied by the solar hybrid system. The generator cannot respond fast enough to these step changes in load, so the battery and inverter are used to provide some of the peak power demands during periods of bulk charging. This enables reliable operation of the system with a generator that is rated at less than the peak load requirements.

The smooth integration of the power from several sources is apparent in Figure 2-51, even at times when the PV arrays are delivering variable amounts of power. This is obvious from examination of the data for August 16, when intermittent cloud cover was quite clearly impacting power from the PV arrays. On sunny days, for example August 17, the battery actually charges for short periods of time, even on the very hot days with high air conditioning loads that are experienced at STAR in August.

Much of the work during FY99 dealt with proper charging and maintenance of the Yuasa cells, was also focussed on the inverter and controller. In the middle of the reporting period, some minor modifications to the equalization charge scheme programmed into the controller were first specified and then implemented. Although the firmware changes required for this were checked out in the factory and at STAR, no long-term testing was possible after their implementation, because of the development work that was proceeding on the rest of the system. Several capacity tests were run during FY99, and as a result of these, about 12 of the 240 cells in the battery were replaced. The capacity of the battery in a test at the end of FY99 was found to be 104% of Yuasa's rated amp-hours.

All of the data being acquired in the testing of the STAR system will ultimately be useful in determining the advantages and disadvantages of using gel VRLAs in solar hybrid systems. In particular, the longer life that is expected from this type of cell when used in an ISOC mode, as compared to other lead-acid battery types, will be the subject of longer term testing at STAR. As yet, however, the focus of the work at STAR has been to attain reliable and unattended operation of such systems, so long-term ISOC cycle testing has not been possible.

Long-term ISOC cycle testing remains a primary goal of the work at STAR, and while progress has been made toward this goal, it has not yet been possible to achieve it. The main issue that still needs resolution is the long-term reliability of the components and the controls of the system. Work for the coming fiscal year will therefore be focussed on finding ways to enable long-term reliable operation of the solar hybrid system and then using the system for ISOC testing of the Yuasa gel VRLA battery.

Integration and Testing of Energy Storage with Flexible AC Transmission System Devices

Flexible AC transmission system (FACTS) devices offer increased flexibility in decentralized control of transmission systems. As the vertically integrated utility structure is phased out, centralized control of the bulk power system will no longer be possible. Transmission providers will be forced to seek a means to get local control to address a number of potential problems such as the following:

1. Uneven power flow through the system (loop flows),
2. Transient and dynamic stability,
3. Subsynchr onous oscillations, and
4. Dynamic overvoltages and u ndervoltages.

Several FACTS topologies have been proposed to mitigate these potential problems, but transmission service providers have been reluctant to install them, usually because of cost. The integration of an ESS into FACTS devices, however, may lead to a more economically feasible and flexible transmission controller, which would have greater appeal to transmission service providers.

The University of Missouri-Rolla (UMR) team has been designing topologies necessary to integrate a BESS into a static synchronous compensator (StatCom). The StatCom is a well known shunt-con nected, commercially available FACTS device. UMR has designed and built a StatCom, which is currently being used to evaluate new design and control strate gies. The first step in this project will be to d evelop interface-power-electronic topologies to incorporate energy storage into the StatCom. This includes potentially eliminating the DC capacitor bank typi cally used for short-term energy storage.

Eliminating the capacitor bank reduces the cost and increases the reliability. After suitable topologies have been identified, both global and local control strategies will be developed to accomplish multi-purpose transmission-level objectives requiring both active and reactive power control. The project will culminate with experimental verification of the iden tified designs. Although the UMR StatCom is rated at 150 kVA, all topologies will be designed so that they are scaleable to transmission-level applications (that is, ratings in the 1- to 10-MVA range). A suit able battery will be supplied by SNL to UMR.

Status

Several significant advances have been made in the last quarter. The most important progress has been the incorporation of the BESS into the StatCom set-up. This step was delayed due to problems with infant mortality of several of the battery modules. This has been corrected and the BESS is now fully functional. The StatCom/BESS system has been successfully operated in synchronism with an external system AC source. Figure 2-52 shows the main components of the integrated StatCom/BESS system layout in the UMR laboratory.

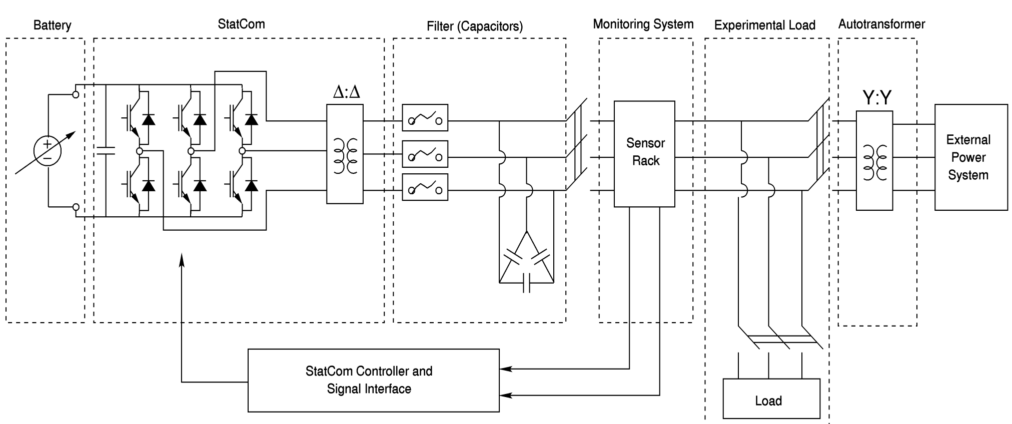


Figure 2-52. UMR Statcom/BESS System Layout.

The battery set shown in Figure 2-53 was constructed by Omnion and consists of 17 Trojan VRLA super-gel batteries in two strings supplying 204 -V DC to the StatCom. The DAS shown in Figure 2-53 was constructed to monitor the battery voltage and string currents. Two current sensors are used to measure the string currents. A signal interface board converts the current signals into voltage signals and filters the high-frequency noise. A thermometer with two thermal se n-sors is used to measure internal battery rack and amb i-ent temperatures.

Figure 2-54 shows the front panel of the StatCom. The top rack houses the StatCom sensor rack that monitors the StatCom voltages and currents, including the three phase voltages and currents, the DC voltage and the DC current. The sensor rack is shown in detail in Figure 2-55. The middle two racks house the converters. Only the upper converter rack is being used in this project. This rack, shown in Figure 2-56, contains six insulated gate bipolar transistors (IGBTs), the DC link capacitors, heat sinks, and control interface. The bottom rack houses the three-winding transformer (not shown).

Along with the above components, a bank of three-phase 150uF capacitors is placed between the StatCom and the monitoring and control system to improve the integrity of the waveform on the system side. The monitoring and control system consist of two M5000 boards: one for data acquisition and pre-processing and the other for sine-triangle pulse width modulation (SPWM) signal generation. The signal interface board is designed to provide digital and analog signal isol a-tion for the PC as well as analog filters for the analog signals. It generates the synchronous signals for the SPWM generator and the data acquisition board.

The most important result has been the exper i-mental verification of the proposed control methods with the StatCom/BESS connected to the external AC system. This required one modification to the local

Figure 2-53. Battery Rack (left) and DAS (right) at UMR.

Figure 2-54. StatCom Front Panel at UMR.

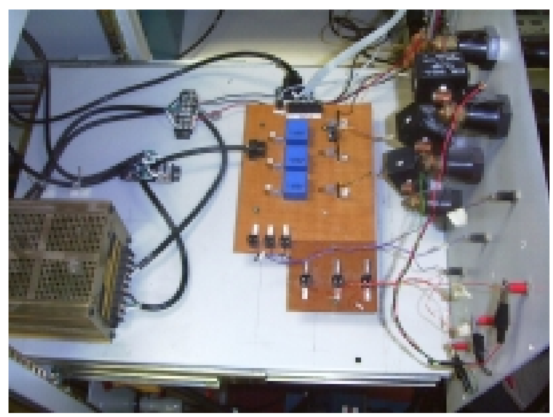


Figure 2-55. UMR StatCom Sensor Rack.

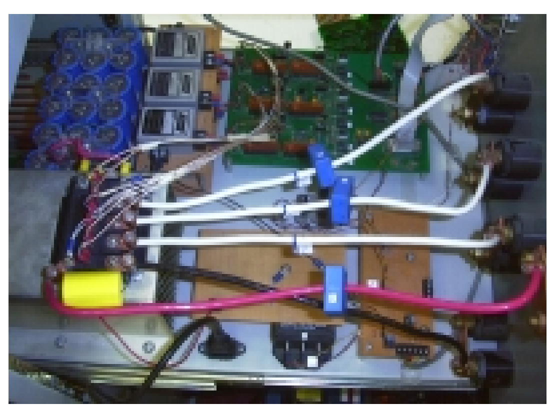


Figure 2-56. UMR StatCom Converter Rack.

control method and the development of a global control scheme. The control of the StatCom/BESS may be divided into local and global control. The global control algorithm is responsible for maintaining system performance according to some pre-set or user defined scheme. The global controller's function is to provide the local controller with the desired commands to achieve the system objectives. This aspect of global control will be discussed in greater detail in the following section.

The local control objective is to interface with the global controller and to provide the switching commands to the inverter. A modified SPWM was developed to switch the IGBTs to synchronize the StatCom/BESS with the external system, and control the output voltage phase angle and magnitude of the StatCom/BESS. Typically, a true SPWM would be ade-quate for control. However, special circumstances re-quired a modified SPWM in this project. In the experimental set-up described previously, the battery voltage is 204 V. In order to connect directly to the 230-V AC system, it was necessary to use the StatCom to boost the output voltage to this level. This was accomplished by boosting the range of the modulation index k. The modulation index k is in the linear region between approximately 0.5 and 1.0. As k increases beyond 1.0, the maximum value of the reference signal is greater than the magnitude of the carrier signal (the triangle waveform) and the voltage magnitude output begins to level off and the voltage output cannot be further increased. The range of the modulation index k was boosted by roughly 15.5% by using a new reference signal other than a sinusoid waveform. The new reference waveform is a sinusoidal signal augmented by a scaled 3rd harmonic waveform. By using the combination fundamental/third harmonic waveform, the modulation index of the fundamental component was increased beyond 1.0, while the maximum value of the reference signal remained below the maximum value of the carrier signal. The third harmonic signal is eliminated when it passes through the interconnecting transformer so that the output is not corrupted. Figure 2-57 shows a typical sine-triangle waveform, and Figure 2-58 shows the modified SPWM modulation signals with the third harmonic waveform imposed upon the fundamental sinusoidal waveform.

The validity of the modified SPWM was verified experimentally. Figure 2-59 shows the increased linear operation range using the modified SPWM. Note that the linear region for k is increased from 1.0 to approximately 1.15, and the output voltage is increased to 135 V (line-to-neutral) or roughly 235 V (line to line), which is sufficient to connect into the laboratory AC system.

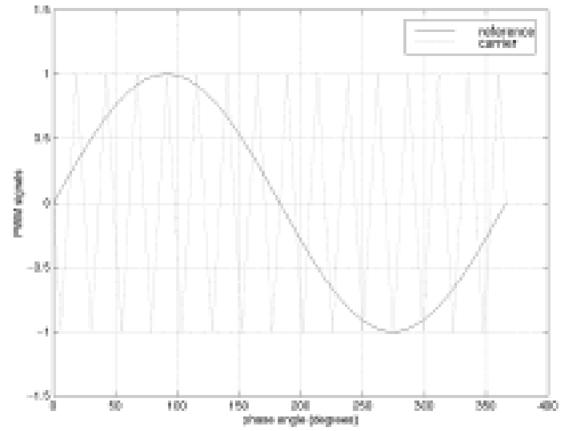


Figure 2-57. Typical Sine-triangle PWM.

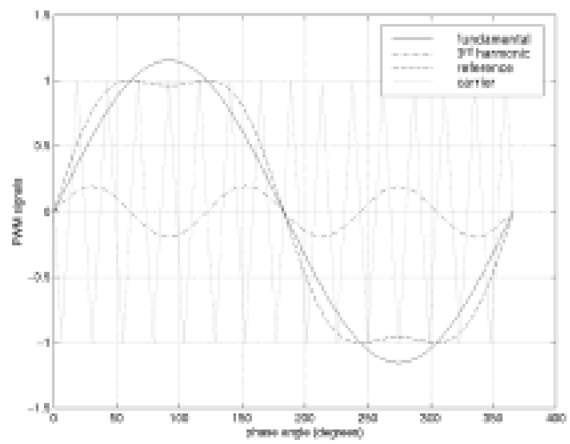


Figure 2-58. Modified SPWM.

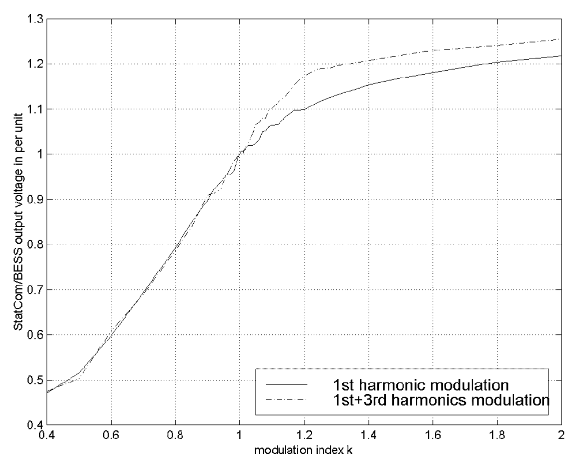


Figure 2-59. Relationship between Modulation index *k* and StatCom/BESS Output Voltage.

Figure 2-60 shows the resultant experimental waveforms from the commanded active and reactive root mean square (RMS) power changes, much as would be commanded from the global controller. In Figure 2-61, the commanded active power is changed from a steady state-value of 0 W to a discharge of 500 W. Similarly the reactive power is instantaneously changed from 0 to 500 Var discharge. The StatCom/BESS responds rapidly to changes in commanded values. The effect of the proportional integral (PI) controller is evident in the slight overshoot in the initial response, but the signal decays rapidly. The StatCom/BESS is then commanded to rapidly charge by the same amount of active and reactive power and then return to zero. The experimental measured responses show good agreement with the predicted dynamic responses from previous simulation results already reported.

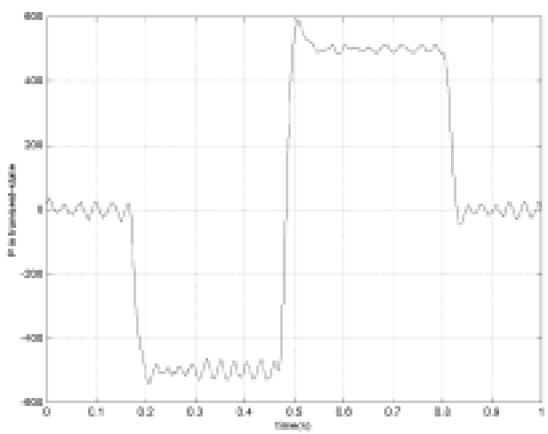


Figure 2-60. Measured Results for Active Power Control.

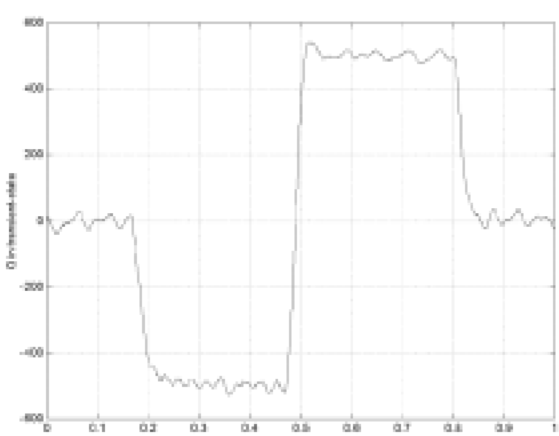


Figure 2-61. Measured Results for Reactive Power Control.

The requirements for a StatCom/BESS global controller are designed to stabilize the power system. Possible applications of the StatCom/BESS include voltage and steady-state power flow control, frequency regulation, oscillation damping, and transient stability improvement. These requirements may change based on the size and placement of the StatCom/BESS within the power system. In this project, two applications of the StatCom/BESS were explored: transient stability improvement and oscillation damping. The global controller was developed based on a single-machine-infinite-bus representation of the power system with the StatCom/BESS at the mid-point between the generator and the infinite bus as shown in Figure 2-62.

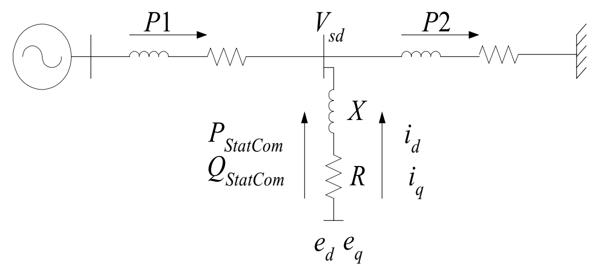


Figure 2-62. One-Machine-Infinite-Bus Power System with StatCom/BESS.

A power system case is simulated by PSCAD/ EMTDC software to verify the effectiveness of the proposed global control strategy. In this example, a three-phase to ground fault occurs at the StatCom/BESS connected bus. The fault is cleared after 0.1 seconds. The global control objectives are to damp generator rotor angle oscillation, and maintain voltage magnitude and active power P2. The global control results are shown in Figures 2-63 through 2-66. After the fault is cleared,

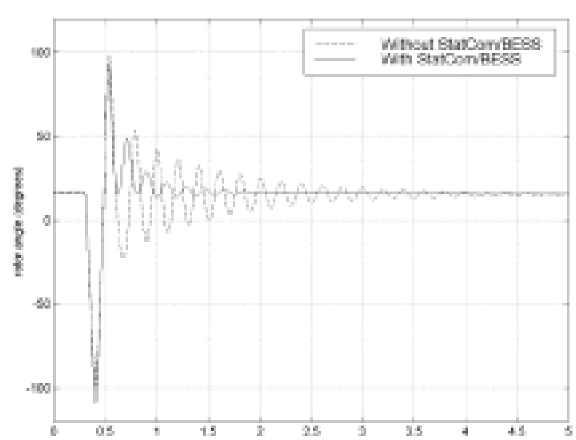


Figure 2-63. Generator Rotor Angle.

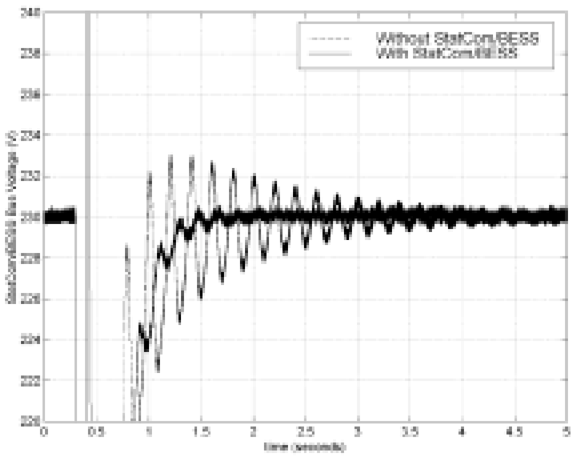


Figure 2-64. StatCom/BESS Terminal Bus Voltage.

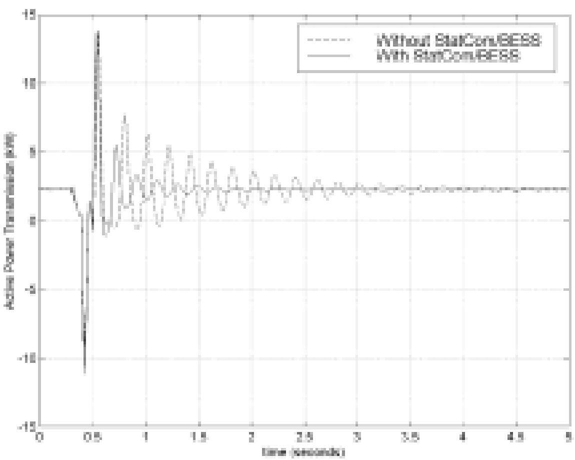


Figure 2-65. Active Power in Line 2.

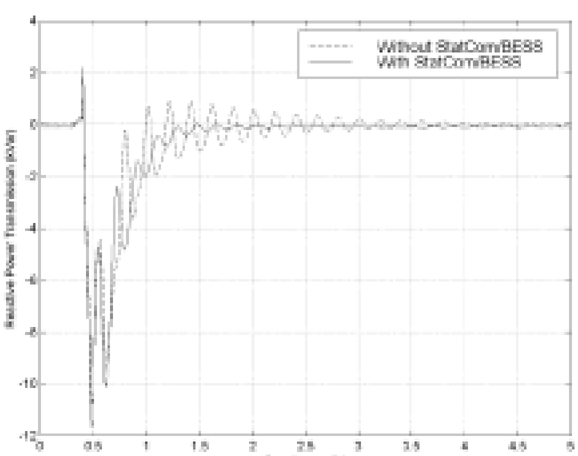


Figure 2-66. Reactive Power in Line 2.

the StatCom/BESS is able to effectively damp the oscillations in both voltage and angle and hold P, Q, and V at the desired values, resulting in enhanced transient stability of the power system.

This project firmly established the viability of using a StatCom/BESS to enhance bulk power system operation. Several local and global controls were proposed that have been shown, via simulation and experimental verification, to be effective in transient stability improvement and oscillation damping.

To this point, all local and global proposed control techniques have been based on decoupled PI-control. These controllers should be extended to include more sophisticated control methodologies such as state feedback or nonlinear control to enhance performance.

While the StatCom/BESS has been shown to be effective in oscillation damping, it is desirable to develop a controller that will have a greater damping effect during the "first-swing" of the post-fault oscillation. The dynamic performance of the StatCom/BESS must also be compared to the dynamic performance of other FACTS devices including a stand-alone StatCom and the unified power flow controller (UPFC) to fully assess the benefits of this topology. Also, the sizing and placement of the StatCom/BESS must be explored before this technology can be utilized effectively by industry.

RAPS Testing Methods Development

The ESS Program continues to coordinate with staff from ILZRO on several collaborative projects. Each project is being co-funded by ESS and by ILZRO at varying levels of cost sharing ranging from 50-50 to 80-20, with ILZRO taking the lead in some projects and ESS in others. A project to define an international standard test-cycle regimes for RAPS has begun scheduling goals for drafting test procedures and reviewing the procedures.

Status

During FY99, the RAPS testing methods development project evolved significantly and began to cement relationships with standards organizations. The goal is to prepare documents that will lead to RAPS design and certification guidelines. With major involvement of the project's co-sponsor, the ILZRO, and Energetics, contractor to both SNL and ILZRO on this project, substantial planning was done, documents were prepared, and standards organization interfaces were established. A major decision was made to integrate this project with the existing infrastructure of the Institute of Electrical and Electronics Engineers (IEEE) Standards Coordinating Committee (SCC) 21, Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage. This committee has several standards documents already in preparation or approved that will contribute to RAPS design, testing, and certification guidelines. The documents in process all relate to PV energy systems with battery storage used in a stand-alone mode (no utility connection). SNL, ILZRO, and Energetics will contribute to the PV/battery documents, and will prepare new guidelines for RAPS systems–those that use a renewable generation resource, energy storage, and a fossil-fueled generator in a stand-alone mode.

Additionally, contact was made with IEEE SCC 29, for Stationary Batteries. While this group does not prepare standards for RAPS systems, its heavy involvement with battery technology requires coordination on terminology and other battery issues.

In order to build the necessary relationships with the IEEE SCC 21, two meetings of the Energy Storage Subsystems Working Group were attended during the year. The first was in June 1999, and the second in late September 1999. The project is providing a secretary to take notes and publish minutes of each meeting.

Based on the results of these meetings, a plan was prepared for integrating the RAPS test project with existing SCC 21 standards, and for preparing new standards within the auspices of SCC 21. The plan divides the systems by application: PV/battery stand-alone systems and hybrid (PV-battery-diesel generator) RAPS systems. The following list describes the existing standards and proposes several new ones to complete the needed documents.

PV-Battery Stand-alone System Standards

1. Std. 937-1987: IEEE Recommended Practice for Installation and Maintenance of Lead-Acid Batteries for Photovoltaic Systems.

2. P1013/D6: Draft Recommended Practice for Sizing Lead-Acid Batteries for Photovoltaic Systems.

3. P1144: Recommended Practice for Sizing of Industrial Nickel-Cadmium Batteries for Photovoltaic Systems.

4. Std. 1145-1990: IEEE Recommended Practice for Installation and Maintenance of Nickel-Cadmium Batteries for Phototvoltaic Systems.

5. P1361: Guide for Selection, Test and Evaluation of Lead-Acid Batteries Used in Stand-alone Photovoltaic Systems.

6. P1526: Procedures for Determining the Performance of Stand-alone Photovoltaic Systems.

7. New Project Authorization Request (PAR): Guide for Array and Battery Sizing in Stand-alone PV Systems.

Hybrid Stand-alone System Standards

1. New PAR: Guide for Sizing Hybrid Stand-alone Energy Systems.

2. Concept for PAR: Guide for Test and Evaluation of Hybrid Stand-alone Energy Systems.

3. Concept for PAR: Recommended Practice for Installation and Maintenance of Hybrid Stand-alone Energy Systems.

During the SCC 21 Energy Storage Subsystems meetings, the working group discussed and reviewed these existing documents and proposed the two new PAR documents. The existing document 1013 does not assist in sizing the PV part of the system. Neither does 1013 address battery charging with PV. A new approach is needed for sizing batteries in stand-alone PV and RAPS systems. A design document that also considers cost trade-offs is needed.

At the suggestion of personnel from the RAPS project, two new IEEE standards will be proposed: one for sizing stand-alone remote PV systems, and one for hybrid stand-alone systems. The idea will be to create one document that guides the design of systems with a renewable source (e.g., PV, wind, etc.), an ESS (e.g., batteries, flywheels, high energy density capacitors, etc), a power conversion subsystem (e.g., inverter, converter), and controllers (e.g., charge controllers). The other document would also consider a fossil-fueled generator such as a diesel, propane, or natural gas generator. Both documents will be prepared in a modular manner with the first versions only including PV and lead-acid batteries; in the case of the RAPS document, diesel generators will be included. Other technologies will be added later. The group recommended that the documents focus on specific sizes and applications and then add other size ranges and applications later. For stand-alone PV systems, the size should be no larger than 2 to 4 kW. A study is in progress as part of this project to better define the application requirements and size ranges for RAPS systems. The results of this study will be used to focus the RAPS design document.

In addition, a draft document prepared by ILZRO, "Elements of a Recommended Design Practice for Community Scale RAPS with Only PV Generation," will be used to contribute to both the PV/battery doc u-ment and to the RAPS document. The ILZRO doc u-ment contains significant engineering details on sizing components and design trade-offs necessary for co m-plete system guidelines. These elements are lacking in existing draft documents and will be a valuable contr i-bution. In addition, the ILZRO RAPS testing commi t-tee formed two years ago has reaffirmed their commi t-ment to reviewing and contributing to the RAPS sta n-dard. This interface will be critically important for properly developing the design guidelines for hybrid systems.

Applications for the new IEEE standards will be made in early FY2000. Once approved, work on the first draft of each standard will begin. SNL, ILZRO, and Energetics will team to develop the RAPS design guidelines during FY2000.

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3. Components

Introduction

Work in the Components element focuses on improving the subsystems that make up energy storage systems: improved devices are developed and evaluated, i.e., storage (for example, battery), electrical equipment (power conversion), and controls. The ESS Program is developing and evaluating storage and other components that cost less, have higher performance, and are better integrated with other parts of the system than those now available.

As part of its technical mission in support of the ESS Program, SNL performs in-house battery evaluation tasks. These tasks use specialized and unique facilities and capabilities established during many years of program activities in battery and other storage technologies. Controlled laboratory tests provide the best method of determining capacity degradation rates for discovering mechanisms to understand the relevant cause-and-effect relationships. These independent, objective tests use computer-controlled testers capable of simulating application-specific test regimes, and they provide critical data for the assessment of the status and probable success of these technologies.

Development

Advanced Energy Storage Development

In FY97, the ESS Program started to analyze advanced storage technologies (SMES, flywheel, double-layer capacitors [DLCs], etc.) and determine the true state of the art of each technology for both capability and cost. R&D is contingent upon the conclusions of these studies. The overall approach to R&D for all advanced technologies will be to (1) identify the industry drivers for each technology, and (2) estimate the compatibility and value of these storage technologies for each of the 13 storage applications (identified in the Opportunities Analysis performed earlier) * as well as for the combined applications.

Based on the results of these R&D studies, plans were made for one or more contracts to be competitively placed with suppliers of the technologies that show the most potential. Some of these contracts will be to supply SNL with hardware for testing. Other contracts may fund small demonstrations with potential users in applications that show the greatest potential for benefits.

The goal of the advanced energy storage (AES) component development project is to support the improvement of AES components. Commercial battery technologies are not included in the scope of this project.

Status

In FY99, the ESS Program issued an RFP and funded three companies (Saft, U.S. Flywheel, and Boeing) to conduct the first phase of a possible multi-phase research project to develop and test components that are large enough to be used in field demonstrations. In Phase I, contractors identified target applications and characterized the applications in terms of benefits and requirements. The contractors then developed storage component specifications and conceptual designs for the most beneficial applications based on state-of-the-art technology. Both prototype and production-scale costs for the technology were then estimated. Finally, contractors created a component development plan and schedule to develop the technology to the prototype field-testing stage.

Work on Phase I was completed at the end of FY99. Saft presented results on an advanced battery technology and U.S. Flywheel and Boeing each presented results on flywheel technology. The final reports documenting this work will be published at a later date. Below is a brief summary of each contractor's Phase I work.

Saft

Lithium-ion (Li-ion) battery technology has received commercial recognition by the portable battery industry; however, larger cells and batteries are still in the development stage. During Phase I of this project, Saft demonstrated the feasibility of Li-ion technology for ESS applications, identified a suitable target application for the technology, and then developed a test plan and schedule for demonstrating a prototype system, as required by the RFP.

* P. C. Butler, *Energy Storage for Utility Applications: Phase I-Opportunities Analysis*, SAND94-2605, October 1994.

Feasibility of Li-ion Technology for Energy Storage System Applications

The main advantages of a Li-ion system over conventional batteries are their high-energy density and good cycle life. Table 3-1 shows the energy density and specific energy of Li-ion batteries compared to other types of conventional and advanced batteries. Li-ion batteries also provide good deep-discharge cycling capability. This technology's shallow cycling performance is shown in Figure 3-1. It shows results of 40°C cycling smaller (700-mAh) Saft cells at 10% DOD at a 2C rate. The cells are given a 100% diagnostic discharge every 10,000 cycles. After an initial increase in impedance, the cell characteristics stabilized, and there was almost no capacity fading. Finally, compared to conventional battery systems, Li-ion systems are relatively maintenance-free. The Li-ion cells are hermetically sealed and are non-aqueous. Therefore, there is no electrolysis, no gassing, and no losses from the system. The cells require electronic controls to prevent overcharging. Because these controls monitor the voltage and temperature of the cells continuously, the surveillance is automated. Consequently, while some monitoring of the system is required, "maintenance" is not.

The two major concerns with the Li-ion technology are cost and safety. For the most part, none of the materials used in these batteries has an intrinsically high cost. However, many of the materials are unique to this technology and have no other industrial application. The result is that the cost of these batteries is quite sensitive to volume. While portable Li-ion batteries remain expensive compared to other technologies, the production cost has fallen about 30% in the last two years. This is expected to continue, particularly as production volume increases for larger cells. Eventually, cost studies predict that Li-ion batteries will have an equivalent life cycle cost to lead-acid.

In the past, the main safety concern with rechargeable lithium batteries was associated with metallic lithium negative electrodes. Charge/discharge cycling

Table 3-1. Energy Density of Li-ion Batteries Compared to Other Batteries

	Energy Density (Wh/liter)	Specific Energy (Wh/kg)
Valve-regulated lead-acid	70-86	33
Nickel-cadmium	85	42
Nickel-metal hydride	135	65
Lithium-ion	230	130

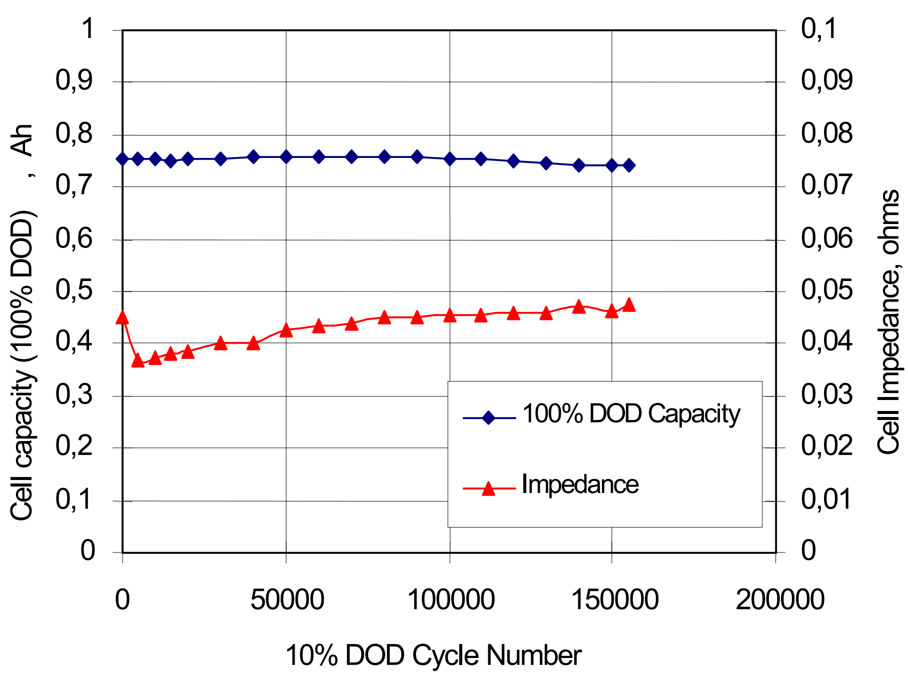


Figure 3-1. Capacity Test (100% DOD) Results for Small Saft Cells Cycling at 10% DOD at 40°C.

caused dendrite formation, and in some cases, highly reactive powdered lithium, which in some cases led to fires. This problem has been overcome in the lithium-ion technology by the adoption of carbon-based negative electrode materials.

Overcharging presents another safety concern. If these batteries are overcharged at high rates (greater than C/5) and the temperature exceeds about 150°C, a fire will result. The organic electrolyte, negative active material, and separators are combustible. This potential problem can be avoided by charge-control electronics. These controls are also required to prevent deterioration in the active materials as a result of overcharging. Saft employs at least two levels of controls:

- The first level of control operates on each cell or grouping of parallel cells. It either switches the cell out of circuit or shunts excess charging current once the cell reaches the maximum charge voltage. This ensures that all cells reach the same state of charge without overcharging.

- The second level limits the overall charge current to a maximum level ($C/5_5$ in the case of Saft's design). Although this level of charging will damage the active materials, it will not allow the temperature to rise to a dangerous level.

Other types and levels of control circuitry are possible. The main point is that redundant levels of control are used. Other protective devices include fusing to prevent damage due to short circuits, and a safety valve to prevent cell case bursting. Apart from the end-of-charge control deployed at the cell level (which is more an integral part of normal operation than a safety feature), it should be noted that all of these safety devices prevent damage caused by external means, such as a charger failure.

Target Applications

Based on an evaluation of the data presented in the Opportunities Analysis report,* Saft identified the following target applications for the Li-ion technology:

- Power quality,
- Customer demand peak shaving, and
- Very short-duration peak shaving.

There is a definite need to address power quality issues where an energy storage system could provide ride-through during voltage sags of less than one second. Previous utility experience has been that it is difficult to sell storage for this application, particularly where users have not quantified a direct cost for their power quality problems. Nevertheless, with the increasing sensitivity to power fluctuations of new systems and operations, this application will increase in importance.

Demand peaks have a demonstrable effect on a customer's utility bill. On their own, such charges are not of sufficient magnitude to provide a reasonable payback on the system cost. However, demand peak shaving can provide an attractive additional benefit in a system installed primarily for power quality.

The last possible application would be to mitigate the effects of very short-duration demand peaks, such as motor inrush currents. Where such load spikes have the potential for causing power problems in the vicinity, storage can be a mitigating factor. This application contains elements of both peak shaving and distribution facility deferral. Its importance in a demonstration system would depend on the load characteristics of the chosen customer.

An energy storage system that combines the capability to ride through voltage sags with demand peak shaving can provide real and immediate savings for the consumer. An additional capability to handle load spikes would be beneficial. The capability of Saft's proposed system to handle various combinations of these loads is discussed below.

General Specifications

To design and develop the demonstration project, Saft identified two potential industry partners. One partner would supply the system equipment (power electronics, etc.), and the other would act as the system integrator. At the conclusion of Phase I, a candidate demonstration site had not yet been identified.

Without a specific customer/demonstration site, the final specifications of the proposed system are subject to change. General specifications are that the proposed system will have an output of 400 to 500 kW, and a battery storage capacity of 67 kWh. The system will operate in the on-line mode, so the output will be sized for the entire facility load (or that portion of the load that is sensitive to power problems). Output is at 480 Vac and the system will be located on the customer's premises. Saft has two specific designs in mind to meet these specifications should further work on this project be funded.

* P. C. Butler, *Energy Storage for Utility Applications: Phase 1–Opportunities* Analysis, SAND94-2605, October 1994.

The development of these designs would occur in two stages. The first would comprise battery development and testing at Saft. The second stage would involve system integration and on-site testing at the customer's location.

U.S. Flywheel Systems, Inc.

U.S. Flywheel Systems (USFS) proposed a flywheel energy storage (FES) system for this contract. Their design, however, is fundamentally different from the one described by Boeing. Boeing proposed a system based on a single, large flywheel; the USFS system, which is described in more detail below, is based on combinations of many smaller flywheels.

Target Applications

Flywheels have certain operating and performance characteristics that are important when identifying target applications. Flywheel systems are compatible with the full range of expected environmental conditions, and shipping, orientation, or reasonable shock and vibration do not generally affect their operation. USFS has developed the concept of fiber rotor benign failure, which is designed into the rotor fabrication to produce a harmless failure. Consequently, one of the main safety concerns for FES, explosion containment, is not expected to be an issue, even with mass usage. Another interesting characteristic of FES is the ability to separate specific power and specific energy as design entities. This ability is significant when designing a storage system for a specific application.

The above characteristics lend themselves to a variety of applications including space (satellites), hybrid electric vehicles (HEVs), utility energy storage and UPSs, and marine and oceanic applications. Requirements for energy storage for these applications are summarized below.

- Space requirements: highest reliability, highest efficiency, highest cycle life, highest specific energy and specific power, and requires magnetic bearings with costs being less important.
- Ground hybrid vehicular requirements: high human safety, very high specific power, very high cycle life, shock and vibration resistant, insensitive to temperature extremes, low cost, possibly magnetic bearings, high production.
- Ground utility/UPS requirements: high human safety, highest production, designs considering ranges of very high specific power and/or specific energy, must be lowest maintenance, must be resistant to the broadest range of environmental extremes, must be fully automatic to grid support, must be price competitive, and must be easily shippable. Large production volumes may justify special magnetic bearings.
- Marine and oceanic requirements: very high human safety, insensitive to temperature extremes, lowest maintenance, very high specific power and/or specific energy, and may justify magnetic bearings.

Basic Design Considerations for Stationary Energy Storage

It was described above that there is a wide range of applications for FES systems. However, the objective of this study was to determine FES compatibility with stationary energy storage applications.

A drawing of a typical USFS module is shown in Figure 3-2; the major components of the module are outlined briefly below.

Rotors: These are solid isotropic materials made from steel and aluminum. Also, fiber-composite rotors (some multi-rim) comprised of glass and many different graphite materials. A great percentage of these were dissected for destructive testing; others were spin-tested to destruction. Still others were integrated into functional operational modules.

Hubs: Isotropic materials on which the rotors were mounted. Numerous designs were employed (some were multi-piece) and were connected to, or were a part of, the flywheel shaft assembly.

Shaft: This assembly protrudes through both ends of the rotor/hub assembly. Each end accepts the bearings (magnetic or mechanical) and the lower end accepts the motor/generator rotor.

Touch down Bearings: Alternate mechanical supports for the magnetic bearings. They are used during shutdown, storage, or as a safety feature for magnetic bearing (MB) malfunction. Thus far all MB design flywheels are vertical axis machines. Some of the mechanical bearing machines are horizontal axis configurations.

Motor/Generator: This unit has a stationary stator with the rotor turning and with the flywheel rotating assembly. The motor/generator (MG) is the unit that determines the specific power of the whole system and is in effect independent of the rest of the assembly.

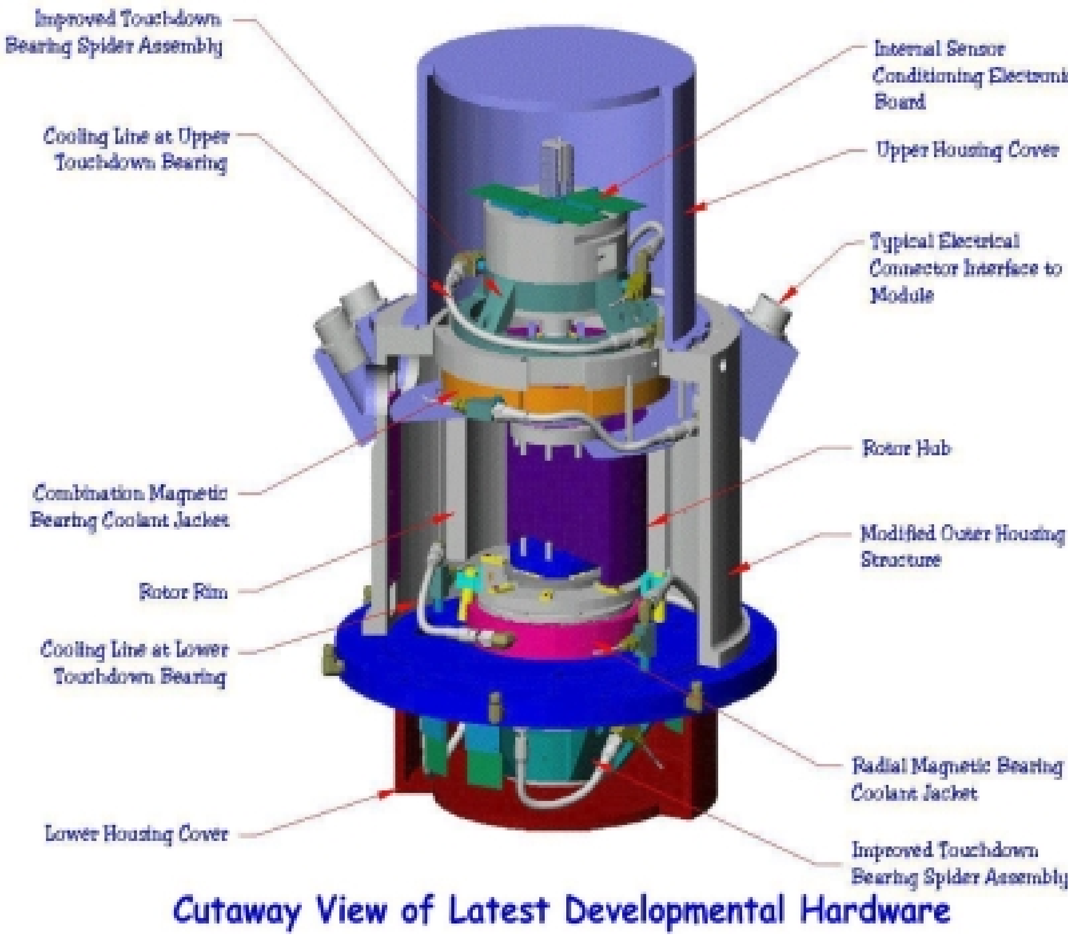


Figure 3-2. Typical USFS Flywheel–Cutaway View.

Magnetic Bearing

An efficient FES system requires exceedingly high rotational speeds. Studies show the higher the speed, the higher the overall cost (up to a point) and system efficiency. It is also shown that mechanical bearing cost can quickly reach a practical limit due to the bearing manufacturing tolerance limits with load and life considerations. USFS MBs have the load-centering power to shift rotor rotation about either its geometric or mass center axes, or anywhere in-between. Mechanical bearings, on the other hand, have no choice in shifting the rotational axis to a more favorable position, nor do they have holding accuracy by an order of magnitude as related to either axis. For these reasons it is reasonable to predict that the MB will eventually be the choice for FES in the distant future.

Power Electronics

This subsystem has two major functions in the case of the magnetic bearing FES and a single function for the mechanical bearing version. The common function is to provide two- or three-phase (or DC) from the module to the nearest grid bus (at the proper voltage) and to provide an acceptable link to the motor/generator. If the FES(s) is less than fully charged and the grid has cheap electricity, energy is accepted from the grid and is parceled to the FES(s) until they are fully charged. If the grid is near maximum capacity, the process is reversed, and energy is automatically discharged to the grid until the FES(s) is down to a selected 90 or 95% DOD. This process can be repeated as often as desired without limitation or harm to the FES as long as the MG is kept within its upper temperature limits. A heat pipe cooling subsystem keeps this limit within bounds. The second function of the power electronics for magnetic bearings is to supply power for the bearings and the FES internal instrumentation.

External Housing/Vacuum Enclosure

As mentioned earlier, with proper design, FES burst containment is not a significant issue. This opinion is supported by work on several National Aeronautics and Space Administration (NASA) projects, including the International Space Station, but is generally contradicted in the automotive industry, where every internal combustion engine vehicle produced in the world today has the least safe design—an isotropic metal flywheel. For safety considerations, the ideal housing (and the one USFS recommends) should have the following characteristics:

- Long-duration, high-vacuum integrity and electrically nonconductive,
- Ability to serve as partial vibration damper,
- Low heat transfer, ease of installing internal and external brackets and fittings,
- High resistance to external corrosion and abrasion,
- Nonbiodegradable and resistant to soil chemistry, and
- Structurally tough, lightweight, high-strength, and inexpensive.

An examination of the desired characteristics listed above points toward composite-fiber, wound FES rotor materials. A recommended fiber candidate is E-glass, which has the strength-to-weight ratio of five-and-a-half times that of type 4340 steel. In addition, its cost is roughly half that of steel; therefore, the strength per unit cost is about one tenth that of steel with far better characteristics. Housings are tubular and extra costs would ensue for stock tube shapes. For fiber winding these nonrecurring charges would disappear.

Prototype Design for an Flywheel Energy Storage System for Stationary Energy Storage

The design considerations discussed attempted to describe the various subsystems of a FES system, and to consider the unique possibilities of design variations that can be selected for any specific application. These opinions may not agree with those of other FES manufacturers.

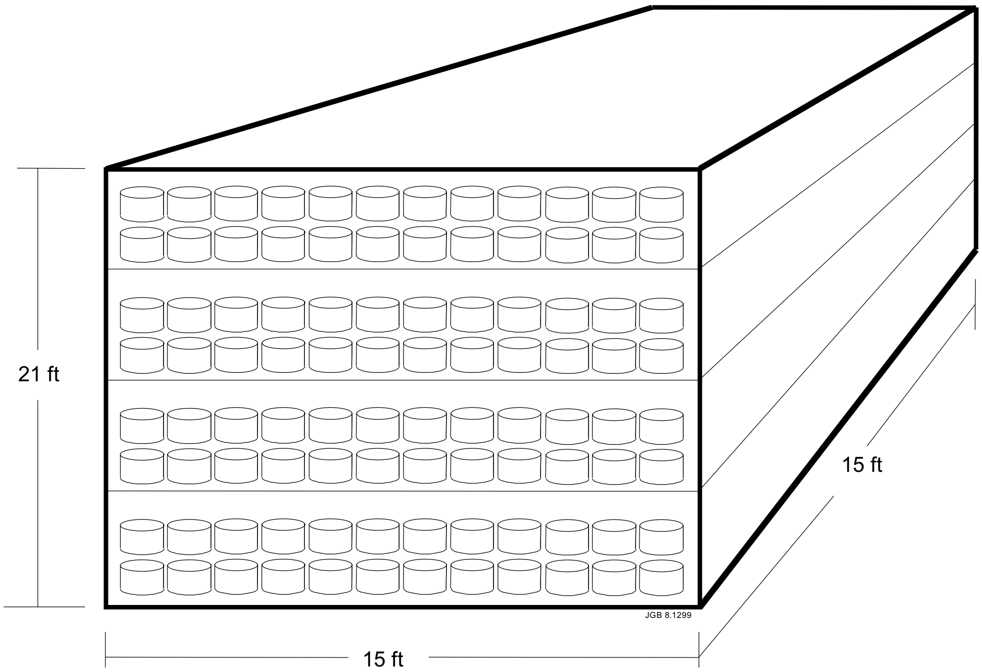
At USFS, the current state of the art would suggest basing system design first on the rotor, a single or dual fiber composite rim with E-glass as the inner material and perhaps capped with a limited thickness of graphite fiber. The materials and processing used for the rotor would also be used for the housing.

The other major component that must be considered is the bearings. A key decision is whether to use magnetic bearings. USFS recommends magnetic bearings over mechanical bearings for the following reasons:

- Magnetic bearings can be made to control the rotor to rotate about either its geometric or its mass center, or in between these two limits. Presume also that some microscopic but unimportant yield occurs somewhere in the rotating mass, thus minutely shifting one or both of these centers. If a mechanical bearing assembly is used, in time this shift could compound the bearing loads and unknowingly affect the bearing's life. Presuming that a failure does not occur, the maintenance costs could then skyrocket at some future date.
- Very high-quality, high-speed, high-load, long-life mechanical bearings are also high cost. Further, these high-speed bearings are sometimes known to fail under operating loads comparable to FES operation. Magnetic bearings never wear out and are primarily dependent on the reliability of the system's electronic components.
- USFS believes that low production costs for magnetic bearings for FES can be achieved and continues to pursue efforts toward cost reduction.

To design a prototype system specifically for a utility energy storage application, USFS first selected a maximum level of energy storage per module—about 1.4 kWh. This level was selected to minimize the flywheel's momentum for safety and containment considerations. Increasing this level would probably rapidly increase developmental cost, possibly exponentially. Also, designing a single large module may eliminate many users with smaller storage needs. Using many small modules, instead of one large one may increase flywheel use and thus could contribute to cost reductions based on high volume production. The lower limit of energy storage would be about 0.3 or 0.4 kWh per module. Another major design consideration was the maximum power at top design rpm. USFS selected a range of 5 to 20 kW.

Figure 3-3 shows a small utility storage building comprising 1.15 MWh of energy storage and lists some additional specifications. The enclosure has a footprint of 15 ft^2, is 21 ft high, and contains 1,152 modules. This modular concept will allow any individual flywheel module to be automatically removed and re-plugged into its required position by an "x-y-z" tram



Sample Specifications

- FW module size: 1.7 ft dia x 2 ft high
- FW energy storage: 1.0 kWhrs useable per module
- Above complex has storage of 1.15 MW hrs
- FW operates to 95% DOD (4:1 speed ratio)
- FW equipped with mag bearings
- Cycle life estimated at 20 to 30 years
- Every module accessible by auto remove/replace
- Each module plugs into special sockets
- Every module has its own separate power electronics
- Every module protected from “crow-bar short”
- Above complex immune to sand, dust, temperature & water
- Only maintenance is feeding “auto load/unload system”
- The above typical facility comprises 1,152 modules

Figure 3-3. USFS Concept for Utility FES Building with 1.15-MWh Energy Storage Capacity.

system. Such removals may be necessary for occasional maintenance. The same technique would be applied to nearby power electronics shed(s). The capacity of this concept could be expanded by multiples of 15-foot cubes, or by fewer layers modules in any single cube.

The power electronics for such a system should be located in an adjacent enclosure. One or more modules would be serviced by separate power electronics system(s), each of which should be arranged for ease of maintenance and/or replacement. If it should turn out that magnetic bearing controllers are cost-effective, then the bearing controllers would be in the same enclosure as the power electronics.

The plot in Figure 3-4 presents major expansions of this modular concept. In this plot, the energy for a complex of flywheels assumed to be located in a square area can be seen up to 50 ft on a side and by two-layer increments up to the full 8-plane (8 layers) as a function of maximum energy storage. What is shown is that 15 MWh of storage can be placed in a relatively small space.

Boeing

The broad goal of this project is to support the improvement of advanced energy storage components in cooperative efforts involving the government, technology developers and manufacturers, and electric power providers. There are still many gaps in the technology supporting advanced storage methods. In the case of flywheels, these range from fundamental material issues such as composites durability to supporting technologies such as bearings, cryogenics, and safety

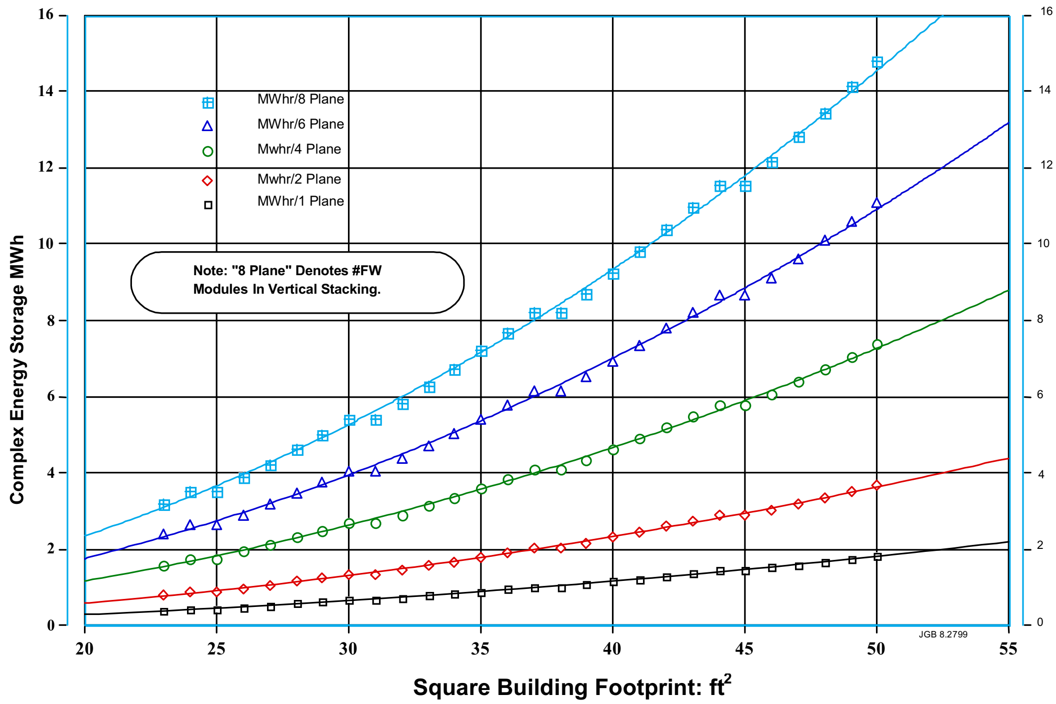


Figure 3-4. USFS Utility Flywheel Multi-MW Footprint Parameter Study.

systems. One of the goals of the component develo p-ment activity is to support projects that will, through a multi-phased approach, result in the development and testing of components that are large enough to be used in field demonstrations—not just "beaker-scale" R&D. Flywheel research is at a stage where the transition to such systems can be made. To do so will require many skills and the coord inated efforts of many participants.

The objectives of Boeing's Phase I effort included completing a survey of potential applications for fl y-wheel storage, selecting a target application for future development, determining which technologies were most in need of further effort, and laying out a rough plan for carrying out development through a successful field demonstration.

Boeing worked with two firms with experience in identification and analysis of power markets to rapidly assist with fact-finding, both for potential target appl i-cations and host sites. Boeing then developed conce p-tual designs for two sizes of flywheel systems and e x-amined manufacturing costs for those systems as projected with learning curves on major components. The specific costs (on a \$/W and \$/Wh) basis were compared with existing solutions now on the market, primarily battery systems. A further narrowing down of the selections was performed to achieve the class of applications of interest. Some of the issues important to development of flywheels for the selected application were then ident ified.

Target Applications

Boeing used the results of two studies and its own research to evaluate possible target applications. The first study, conducted by Energetics, Inc., evaluated data from the World Bank and other studies. This work primarily addressed off-grid power systems, which i n-clude both diesel and renewable generation. The Ene r-getics study shows the enormous potential for storage technologies to improve the capabilities of PV, wind, hydro, and diesel generation sites. Applications range from very small but numerous household and village systems to larger communities, businesses, and military bases, which must be able to operate independent of a power grid. Most of the data in this study were based on PV systems but the storage requirements for other renewable and hybrid systems will be sim ilar.

The second study was conducted by Jack Wood Associates and included a site visit to Kotzebue, Alaska. This study focused on gathering information on several potential applications and host sites for de m-onstrations. The study also provided a variety of su p-plementary information on power generation in Alaska and opportunities for potential state agency involv e-ment.

In 1994 and 1995, Boeing's Defense & Space Systems Group undertook a detailed study of MWh-class flywheels for a centralized load-leveling application. Such wheels would postpone or avoid the need for additional generating capacity and allow current generators to operate more efficiently. The size of the wheel was driven by the economies of scale required for this application. The tremendous leap forward in the size of flywheels, to 15,000 lb/11-ft-diameter rims, was made feasible by two Boeing innovations: the high-critical temperature (Tc) superconducting suspension, and a non-autoclave process for composite ring fabrication.

Boeing and a major utility worked together to define not only the requirements but a detailed plan to obtain needed information and to reduce technical and cost risks. Advanced gas-fired turbines provided the benchmark for pricing. Ultimately it was determined that the market could use several thousand flywheels per year at a delivered price of $400 to $600/kWh. When comparing this target with reasonably aggressive manufacturing cost projections, it was determined that serving large grid-connected applications such as load leveling (LL) may be economically feasible even in the near term. The margin for error was large, however, so it was difficult to make a clear-cut case for immediate investment.

Power quality (PQ) and UPS systems are also interesting applications for flywheels. A capable PQ system is already being marketed by Active Power of Austin, Texas. The steel wheel, essentially a high-inertia motor on conventional bearings, can deliver high powers for several seconds. Boeing's current focus is toward the substantially increased stored energies attainable with composite rotors, and low-loss/wear-free suspensions based on magnetic technologies. The Boeing/DOE Superconducting Partnership Initiative (SPI) project is ultimately targeting UPS applications with a large emphasis on suitable motor technologies.

After reviewing the reports of Energetics and Jack Wood Associates and previously acquired data from a variety of sources, and Boeing's production cost estimates for different classes of wheels, Boeing was able to determine a more specific application. A summary of the potential market to 2010 is shown in Table 3-2.

Comparable domestic United States applications can be found primarily in Alaska, Hawaii, and some mainland sites such as Indian reservations. While small as a proportion of United States power production, the off-grid component in Alaska comprises roughly a third of the state's total power bill. The cost of power in these areas is now quite high—anywhere from $0.30 to $0.60/kWh. This leads to an acute need for power efficiency and for local means of adjusting to variations in demand as well as generation. Perhaps more important for the future of storage technologies, domestic development and demonstration can serve as a springboard to reach the greater worldwide markets, and can move toward eventually serving grid-connected applications.

The city of Kotzebue, Alaska, has a total load of 1.5 to 3 MW that is primarily diesel-generated but includes several hundred kW of wind generation. Kotzebue falls somewhere between Applications IV and V in Table 3-2. There is a move toward more wind generation in Alaska, with more "high-penetration" installations that will use diesel as little as possible. The success of these installations will rely heavily on storage technologies being available as well as efficient backup strategies employing diesel. Without storage, a reliable system would require nearly constant operation of a diesel generator at some low fraction of its rated power. This is highly inefficient, as is shown in Figure 3-5. A preferred strategy is to use storage to serve the load in all but prolonged drops in available wind energy.

A flywheel system meeting the requirements of a high-penetration wind-generation site thus presents itself as an excellent target application on which to base future development efforts.

Power System and Storage Unit Description

The general specifications for a wind/storage/diesel system are shown in Table 3-3 below. This represents a small but practical system for a cluster of several homes or a small business center. It would use commercially available wind and diesel components. The minimum stored energy requirement is about 3 kWh. If up to 6 kWh is available, then several operating options will be available. The system could sustain longer drops in wind speed (for at least 30 minutes), provide higher peak power capability, or operate in conjunction with a second wind turbine in a larger system.

The conceptual design of a flywheel storage unit for field testing is described below and shown in Figure 3-6. Major components include the rotor, the bearing systems, the containment and vacuum shells, a motor/generator with its controller unit, and the charge/discharge unit.

Composite Rotor: While it may seem that an energy storage ring should be made of dense materials, in fact the opposite is usually true. This is because stored energy increases as the square of the velocity but only in proportion to mass. A wheel made of dense materials

Table 3-2. Off-grid Storage Applications, Their Requirements, and Potential Markets to 2010 According to Boeing

Application	I. Single Home: Developing Community	II. Developing Community: No Industry	III. Developing Community: Light Industry	IV. Developing Community: Moderate Industry	V. Advanced Community or Military Base
Storage System Attributes	0.5 kW 3 kWh	8 kW 45 kWh	40 kW 240 kWh	400 kW 3600 kWh	1 MW 1.5 MWh
Power	Base: 0.5 kW	Base: 5 kW Peak: ≤8 kW	Base: 10 kW Peak: ≤40 kW	Base: 100 kW Peak: ≤400 kW	Base: 100 kW Peak: ≤1 MW
Discharge Duration	5 to 72 hr	5 to 72 hr	5 to 24 hr	5 to 24 hr	0 .5 to 1 hr
Total Projected Number of Systems	47 Million	137,000	40,000	84,000	131,000
Fraction of Market Captured by Storage (%)	> 50	> 50	≈ 30	≈ 10	< 5
Total Number of Storage Systems to Capture Market Share	> 24 Million	69,000	≈ 12,000	8,000	< 7,000

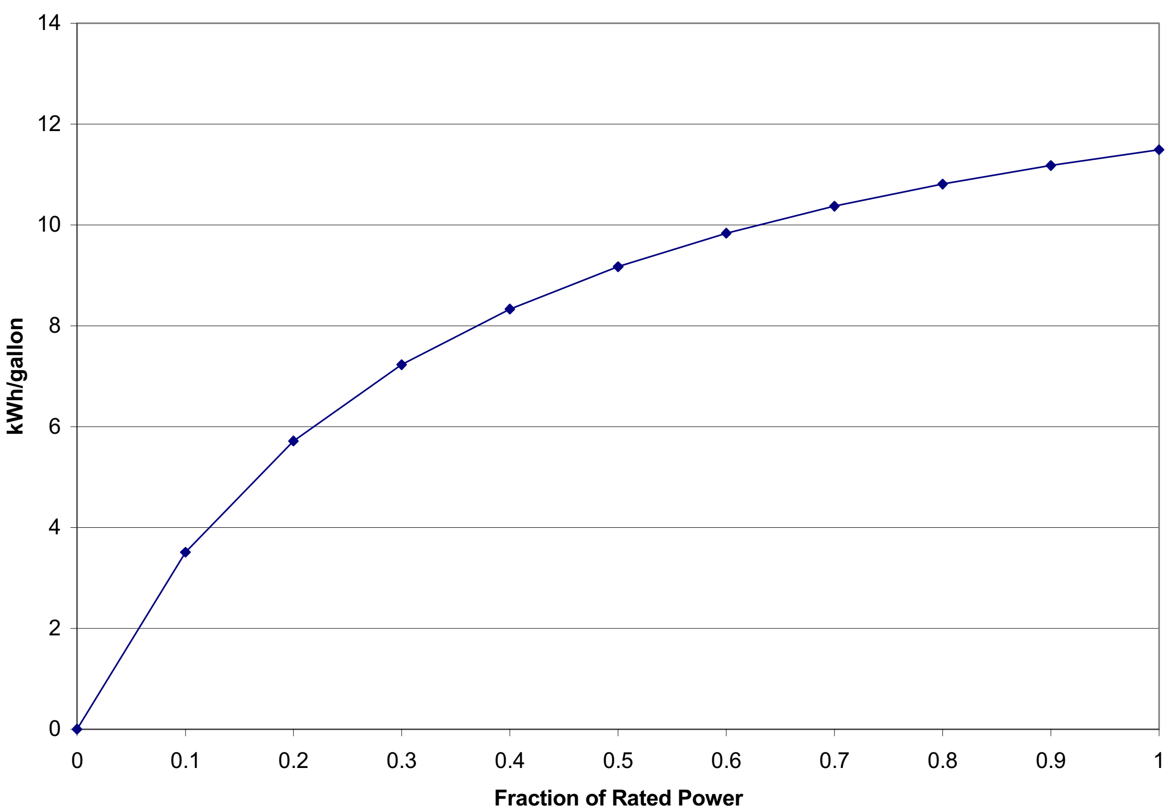


Figure 3-5. Energy Output per Gallon of Diesel Fuel vs. Fractional Utilization of Generator Capacity.

Table 3-3. Boeing Preliminary Specifications for Storage Component of a 12-kW Wind-Generation System with Backup and Peaking Capabilities

Attribute	Requirements	Goals
Configuration	12 kW wind gen. w/storage, part-time diesel backup	same
Net power output	12 kW	12 kW continuous 18 kW intermittent
Discharge time	15 min	15–30 min
Usable stored energy	3 kWh	3–6 kWh
Voltage	Varies; typ. 120 VAC, 3-phase 240 V or 480 V	same
Round-trip efficiency	> 70%	> 80%
Idling loss	Probably < 1 kW	500 W
Footprint	Not critical	< 100 sq ft
Routine maintenance	Typically < 8 hr/month	< 2 hr/month
Reliability	Extremely high	< 3 unscheduled events, 20 yrs.
Site requirements	Aboveground, could be at a local power station	Aboveground, operable in un-heated wind farm shed.
Operating environment	60 – 80°F(approx.)	–100°F – 80°F
Installation time	Not critical	3 days
System life	10 yr	20 yr
Mobility/mass	Transportable by small truck, moveable with hoist	< 1000 lb. excluding electronics

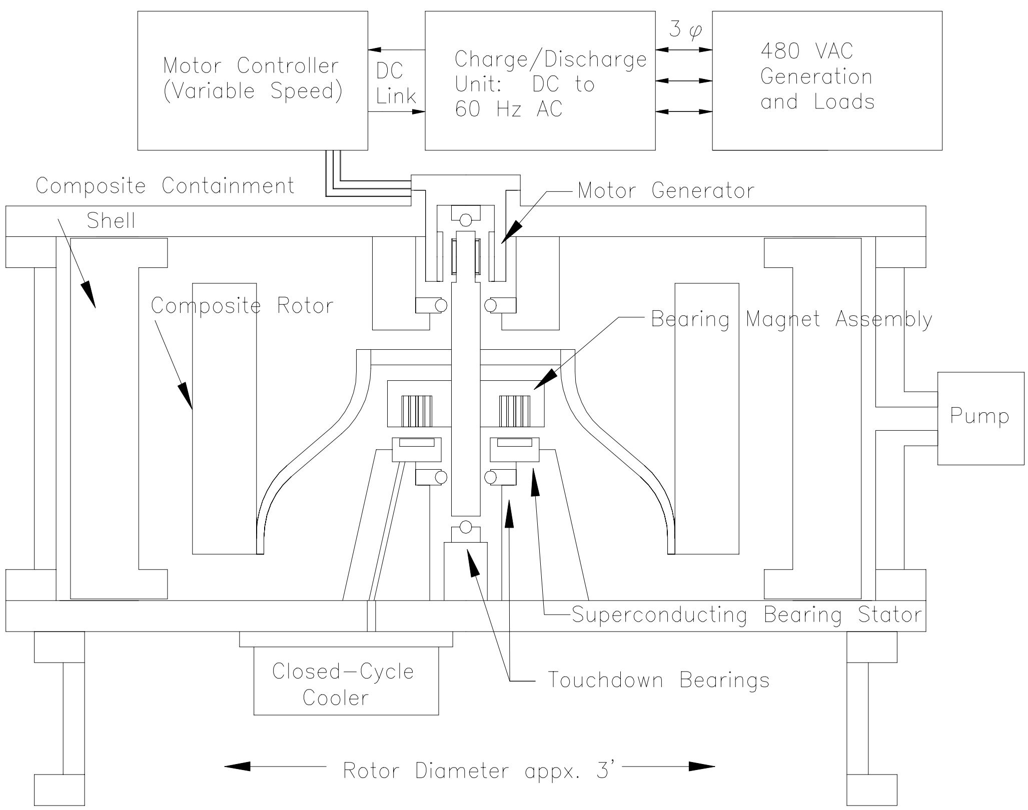


Figure 3-6. Boeing Conceptual Design of Flywheel System for Target Application.

will also be subject to high centripetal forces that will tear it apart at relatively low speeds, while a low-density material can be spun to much higher speeds.

The weight of the rim (Figure 3-7) is important for two reasons. First, it is a major part of system mass in itself. There is approximately a factor of six difference between the mass of a steel wheel and the mass of a high-strength composite wheel storing the same energy. As system capacities become larger, the mass of steel systems will quickly become impractical to transport or to install at most sites. The second reason has to do with the requirements imposed on the rest of the mechanical system, especially the bearings. Very heavy wheels must be supported by mechanical bearings, which are subject to wear, will be difficult to replace, and dissipate substantial amounts of the stored energy. A light wheel, on the other hand, may be supported by a magnetic suspension. Both active magnetic bearings (which use solenoid-like actuators to control the rotor shaft position) and superconducting versions (which act passively) have been demonstrated with composite rotors. The combination of composite rotor and magnetic suspension can almost be taken as the definition of an "advanced flywheel" offering high energy capability, reduced system mass, long life, and minimal maintenance. Power consumption data in magnetic bearings are presented in Figure 3-8.

Hybrid: Superconducting/Permanent-Magnet Bearing: In this application, as with batteries, energy is continuously stored in the flywheel. Therefore, any power drains will have to be made up on a near-continuous basis and will directly impact the sizing of the primary generation source. Until the recent development of bulk superconducting, self-centering high-temperature superconducting HTS bearings, the energy loss associated with both mechanical and electromechanical bearings has been prohibitively high. These losses are often more than 5% of the stored energy per hour. With hybrid superconducting bearings, it is now possible to obtain losses that are as low as 0.1% per hour.

Boeing has fabricated superconducting magnetic bearings and is currently working to improve their quality and reduce their cost. Nevertheless, revolutionary breakthroughs are not required. For example, good-quality materials are already available, and key properties such as critical current density are stable and repeatable. Low drag has been demonstrated using small, single-piece permanent magnet rings. However, more work is required to improve the high-speed capabilities of the magnet assemblies and to understand reliability issues affecting all parts of the bearing.

Motor/Generator: The motor/generator is responsible for providing and extracting energy to and from the flywheel. A variable-speed motor controller transfers power to a DC link and then to a charge/discharge unit to the 60-Hz generators and loads. Key requirements on a motor for this application are the efficiency and ease of control at the speeds required. This will usually result in a motor with a small number of poles. Another important characteristic is the magnitude of destabilizing forces present that can arise due to interactions between permanent magnets and steel in the motor. Types of motors that are suitable for the application include halbach magnet arrays, axial gap DC motors, and some types of radial gap DC motors.

Power Control System: The power control system is the interface between the motor/generator, the generation source, and the system load. The controller uses active rectification to convert the motor/generator's output to a DC level, from which point it can be inverted to supply either single- or multiple-phase 60 Hz power at any desired voltage. The DC link isolates the motor/generator from the grid, letting the controller's firing circuits handle the job of maintaining the correct phase and power factor at the output. The signal must also be clean enough to comply with IEEE Std. 519 for harmonic power distortion.

Reliability and Safety

Long-term reliability requires that the flywheel operate at something less than the maximum stress allowed for the fibers in the rotor, even after taking into account fatigue and creep; thus a rotor failure should not occur within the design life. As a safe guard against failure of the primary bearings, there should also be a touchdown bearing system. These bearings or surfaces also support the wheel during transportation and start-up of the bearing. Even with these safeguards, high-energy wheels should have a backup containment structure to provide protection against any unforeseen release of energy. The energy absorption characteristics of such containment structures and materials are established for steels and some other materials but it is important to keep the weight to a minimum. Innovative designs and approaches are needed in this area.

The designs for major structural components including the rotor, bearing housing, and containment vessel need to be based on proven finite-element computational codes, design-allowable methodologies, and a comprehensive database of metals and composite materials properties. In some cases the data are insufficient, and more materials testing is required.

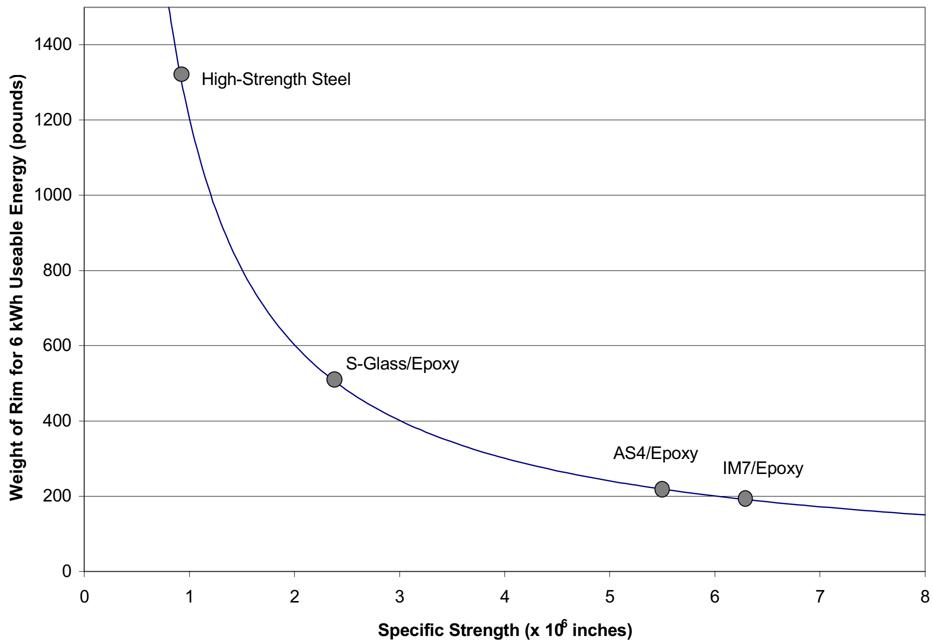


Figure 3-7. **Rim Weight of Thin-Rim Flywheel vs. Specific Strength (yield strength divided by density) for Steel and Composite Flywheel Rims Delivering 6 kWh of Useable Energy. Useable Energy Accounts for 75% DOD, 20% Power Electronic Losses, and Strength Derating of 2.0 for Fatigue and Factor of Safety.**

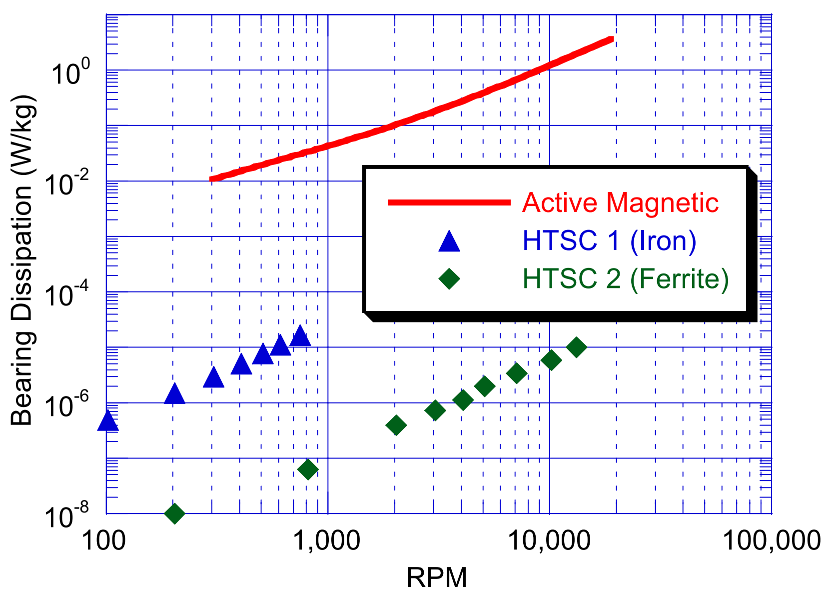


Figure 3-8. **Power Consumption in Magnetic Bearings. Boeing HTS Material Was Tested in Bearings at Argonne National Laboratory; Comparison is to Active Magnetic Bearing Data.**

The Boeing study identified applications suitable for near-term development and demonstration of advanced FES systems. Off-grid power systems have been established at a number of sites in the United States and abroad, and deregulated power markets may encourage greater use of locally generated power. Efficient storage technologies can substantially improve the capabilities and reliability of such systems employing diesel, renewable generation, or both. A number of host sites have been identified that have suitable applications and are interested in participating in a demonstration project.

The overall conceptual design for a flywheel energy system for remote applications is reasonably well defined, although more work remains to be done. The economics of flywheel storage have been studied, beginning with up-front costs, and appear to be favorable, provided that demand will justify production at moderately high quantities. An accompanying study by Energetics, Inc. which will be included with Boeing's final report, looked at worldwide markets for storage and concludes that the demand will in fact be very substantial for favorably-priced units.

Battery Simulator Development and Validation

The ESS Program initiated a collaborative project with the National Rural Electric Cooperative Association (NRECA) in FY97 to develop, validate, and demonstrate simulators of power-quality and peak-shaving systems. The project will provide technical and economic data about peak-shaving and power-quality improvements at electric membership cooperatives (EMCs). More important, the project will introduce a technology assessment that is more exact and no more expensive than a traditional "paper feasibility study."

The ESS portion of the project supports the development and validation of energy storage simulators that will mimic the operation of two BESSs: one that Brockway Standard operates for power quality (PQ2000) and one that Energy United (EU) Cooperative operates for peak shaving. The NRECA portion of the project supports field demonstrations of the energy storage simulators and the development, validation, and field demonstration of a diesel-generator simulator.

The validation and demonstration activities will be hosted at sites to be selected from NRECA members. The project team of Energetics, Inc. and Orion Energy Corporation is developing the simulators, conducting the simulations, and analyzing the output of the simulators. For validation, analysis will compare the simulator behavior with the real energy storage systems. For demonstrations, analysis will determine the financial feasibility of the utility hardware being mimicked.

Status

Development and validation of the battery peak shaving simulator at EU's 500-kWh ESS at its Statesville, North Carolina facility was completed. A draft report was prepared and is under review. During the validation period of August 1998, to April 1999, the utility dispatched the battery system 25 times. The simulator correctly dispatched the virtual battery 13 times. The simulator was off-line for most of the other events because of unanticipated failures of the laptop computer used to run the simulation. When the simulator did operate, the power level was consistently about 30% higher than the actual power level. The computer problem was resolved late in the year when the simulator was redesigned with a rugged industrial processor in place of the laptop. The power level issue was resolved with a software adjustment.

In April 1999, the EU battery was specifically monitored to compare the actual battery output during a peak shave event with the simulator prediction. The simulator battery voltage and current during the discharge were within 5% of the actual values during the two-hour run. The system was also monitored during recharge, and while the voltage predicted was very close (within about 2%), the current (and therefore the power) varied considerably. Again, a software adjustment that takes into account the age of the battery will be made to resolve the discrepancy. A rough evaluation of the economic benefits of the battery indicated the simulator predicted between 10 to 30% excess benefits. This is due to the reduced actual battery capacity compared to the simulation. Software changes to account for the actual battery capacity will correct this offset.

The power quality simulator at Brockway Standard was inoperable until late in the fiscal year. At that time, a separate backup power supply was installed and the validation process continued. The simulator output will be compared with the PQ2000 system data recently obtained for the data management project to complete the validation.

Both simulators will be relocated to demonstration sites for the next stage of the project. An intensive effort is under way to identify and gain the commitment of utility cooperatives to host the demonstration activities. Close cooperation with the NRECA will be necessary for the demonstrations to be successful.

In the diesel generator simulator development and validation part of this project funded by the NRECA, the two EU 500-kW diesel generators at Statesville were used to validate the simulator. These diesels are used to assist in load control and peak shaving. A preliminary report indicates that the diesel simulator is working properly and will be through the validation process in the near future. This simulator will also be relocated to a demonstration site once the validation is complete.

Finally, late in the fiscal year, the NRECA extended its part of the project to include the development of fuel cell and microturbine simulators. The ESS Program also extended its part of the project to include the redesign of the simulator computers (mentioned above), development of a single simulator capable of operating as any of the technologies (battery, diesel, fuel cell, or microturbine) simultaneously, and demonstration of the "universal" simulator at suitable cooperative sites. This work will take place in FY2000.

Valve-Regulated Lead-Acid Reliability Improvement Project

VRLA batteries have been commercially available for more than ten years and have been enthusiastically embraced by users of uninterruptible power supplies because of anticipated reduction in maintenance costs and the smaller footprint available with this technology. As field experience has accumulated, it has become more widely appreciated that VRLA batteries are more sensitive to their operating conditions than flooded lead-acid batteries. This is particularly true under conditions such as elevated temperature or overcharging, which can lead to battery dry-out in starved-electrolyte designs. The result is a shorter than accustomed battery life. Although some VRLA failures may be attributed to abusive environments or improper float-charging conditions, users lack confidence that all of the possible life-limiting conditions for VRLA batteries have been identified. The information on recent failures has made potential utility battery customers, including users of standby power systems, more reluctant to adopt BES technology, particularly if VRLA designs are being proposed.

Because SNL believes that VRLA battery technology offers real advantages in utility and renewable energy applications, a VRLA reliability improvement project was formulated. The primary objective of the project is to determine VRLA cycle and calendar life under typical utility battery operating conditions and use modes. The ESS Program and ILZRO have established a collaboration that addresses VRLA reliability issues. The two organizations generally agree that to address VRLA battery performance issues, the following areas would have to be advanced: optimizing VRLA batteries for stationary applications, establishing the best charge control system, and performing a VRLA reliability assessment. Another important issue is the fact that no method exists to rapidly characterize VRLA battery life. During FY97, the ESS Program finalized plans to develop a VRLA Industry Users Survey in collaboration with ILZRO to begin gathering information from battery manufacturers and users, which is believed to be the necessary starting point in evaluating field reliability information.

A three-phase project was designed to identify and resolve these battery life issues. Phase 1 involves a survey of the industry, in cooperation with VRLA manufacturers and users, to determine objectively and accurately the status of the technology. Phase 2 investigates the critical issues identified in Phase 1 and suggests improvements to the charging methods or other aspects of the technology. Because it is expected that charging protocols will be one of the most critical areas identified for optimum operation, Phase 2 is likely to include a charging study that focuses on those issues. Phase 3 will then attempt to correlate and match the various types of VRLA technologies to the numerous applications now using lead-acid batteries. This will assist users and battery suppliers in selecting a design for an intended application, so that the battery will be appropriately specified.

The Phase 1 study consists of three tasks:

Task 1: Identify VRLA manufacturers and characterize their share of the market by design type and application. Invite each to participate in the study and involve representative users of the products.

Task 2: Develop a detailed list of data needed to characterize the VRLA technology and problems identified by the users. Recover field monitoring data on the systems wherever possible. Organize a database to receive the information.

Task 3: Collect the data, analyze for trend information, and summarize the results in a final report.

During FY98, two contracts were placed by ILZRO to initiate the three tasks in the Phase 1 study. Questionnaires targeting both VRLA manufacturers and users were designed by the contractor and distributed. This analysis will commence as soon as the surveys are received. The survey questionnaires solicit information on battery physical characteristics, electrical ratings, performance and life characteristics, application and operational requirements, R&D database availability, market and sales, and known instances and modes of failure in the field.

Status

Efforts continued in FY99 to encourage return of the surveys, especially by the user group. Manufacturers were also reminded to submit data when they were encountered at professional meetings and during vendor visits. Five manufacturers of VRLA batteries completed surveys that discussed the materials, manufacturing processes, and service-life expectancies of 13 different technologies that serve in stationary applications. The technologies included both gel and AGM designs and the applications included both float and cycling service.

The manufacturers also identified customers who have field experience with their largest-volume product, their best-performing product, and their least-favorable product. The data from the manufacturers' surveys are recorded in an Access database.

The customers who were identified by the manufacturers and those who were identified independently received surveys that are designed to collect data on the field performance of the specific technologies addressed by the manufacturers' surveys. The applications in which the end users employ the VRLA batteries include schools, federal facilities, telecommunication relays and substations, electric utility substations, electric utility emergency start-up/shutdown power, and renewable/hybrid power supplies. One end user declined to participate, citing lack of human resources as the reason. Another user with approximately 400 AGM cells in cycling service has completed and returned a survey.

In the second quarter, project analysts populated the end-user portion of the database with temporary "dummy data" to enable the analysts to test the efficacy of the database queries. The testing process will also help to refine the queries of the database as well. The responses from end users will replace the dummy data after testing of the database is complete.

The time to complete the survey was extended in the third quarter because it was felt that a more assertive approach was required in order to gather sufficient data for the second half of the project. Manufacturers, consumer groups, and other research organizations were contacted and an expanded list of users, including names of individuals to contact, was developed. Based on feedback from recipients, the user survey was reviewed for technical content and revised to make it easier to complete. Revised surveys were distributed to the expanded list of users on this list, and each contact was informed personally of the survey and its purpose. A transmittal letter that was much more emphatic about nondisclosure was included. Follow-up calls were made to each contact, and attempts were made to gather the required data via telephone. Where necessary, visits to sites were made to obtain the data.

By the end of FY99, over 50 end users had been contacted about the survey, and ten had agreed to complete it. This should generate a large enough data set to carry out the trend analysis.

Emitter Turn-Off Switch Development for Power Conversion System

The development of a high-power semiconductor switch, an emitter turn-off (ETO) thyristor, began in the third quarter of FY98. This project entailed the development and testing of a prototype ETO.

ETOs could greatly enhance the power conversion system (PCS), a vital part of the energy storage system used to interface between the storage component (for example, batteries) and the generation and T&D equipment. At the heart of the PCS are the topological connections of high-power semiconductor switches. To meet the demand of these devices, efforts have been made to improve the gate turn-off (GTO) device in the past few years for applications rated in the megawatts. The ETO is a type of GTO device developed at Virginia Tech that could substantially advance high-power ESS applications. Based on the mature technology of current semiconductor devices, the ETO could provide a low-cost, superior solution for megawatt applications.

Significant advantages of the ETO compared to the conventional GTO applications include low driving power, high switching speed, elimination of the dv/dt limiting snubbers, and device-level overcurrent protection. The IGCT also features the removal of turn-off snubbers and high switching speed, but the ETO has several additional features. The ETO has much lower driving power than the IGCT as well as much simpler and lower-cost driver circuitry. The ETO also has the capability to include the on-driver overcurrent protection that the IGCT does not have.

In FY99, this project was extended to the next phase of ETO development. The objective of this phase is to build and demonstrate an ETO in a high-power converter with thermal, electric, control, and reliability all being demonstrated and tested in one unit. The preliminary version started at 100 kVA and is anticipated to gradually move up to high power (1 MVA and higher).

Status

The conventional solution to high-voltage PCSs has been the GTO thyristor. However, these systems suffer several problems because of the GTO's characteristics. First, because of the poor safe operating area (SOA), each GTO requires a large turn-off dv/dt (the change in voltage per the change in time) snubber capacitor that is typically between 2 and 6 μF. This expensive snubber causes large losses that are in proportion to the switching frequency and DC link voltage. Second, a conventional GTO has very long turn-off transient times, including both storage time and minimum off-time. These long switching transient times combined with the above-mentioned snubber loss limit the switching frequency of a GTO application to a very low value, typically around 300 Hz. Third, device protection is very difficult for the GTO system. Even with very high power ratings, the GTO has a relatively low maximum controllable current; any turn-off operation conducted at higher current will destroy the device. Complex protection strategies are required for GTO-based converters at the system level.

With the introduction of high-power, snubberless turn-off thyristor devices such as the integrated gate-commutated thyristor (IGCT) and the ETO, the overall performance of a high-power system can be improved significantly. The dv/dt snubber for the switch can be scaled down or eliminated because of the improved turn-off capability. The switching frequency can be increased because of the removal of the losses in the dv/dt snubber as well as the greatly decreased turn-off time and improved minimum on/off time. Also, the improved maximum turn-off current or SOA combined with the very fast turn-off speed ensures the turn-off operation to protect the device from overcurrent damage.

The first phase of the ETO project at Virginia Tech was the development of a power semiconductor switch, ETO4060, with high voltage (6.0 kV) and current (4.0 kA) ratings. This device was successfully developed, and a sample was tested to its full rating on a pulse-testing circuit. Although the pulse tester can show some useful data, any new device must be tested in a real power converter in order to verify that the device can work with continuous current where thermal issues as well as repetitive stress issues become important.

The current phase of the ETO project is investigating the performance and the impact of a power system by using the ETO as the main switch. A smaller ETO, a 1.0-kA/4.5-kV ETO1045HS, was used to implement a standard phase leg and was used in a DC/DC converter system.

Emitter Turn-Off Snubberless Turn-Off

The device used in the system, the ETO1045HS, is shown in Figure 3-9. The snubberless turn-off capability of ETO1045HS has been verified at up to 3.0 MW of instant power through the ETO during the turn-off transient. The snubberless switching shows only a slight increase in turn-off switching loss compared to that with a 2 μF dv/dt GTO snubber, and shows a dramatic decrease in turn-on loss due to the lack of discharge current from the dv/dt snubber during the voltage fall-time. The overall switching loss is thus reduced when operating in the snubberless condition. Although the ETO can safely turn off without a snubber, the diodes cannot. Therefore a di/dt (the change in current per the change in time) snubber is employed to limit the recovery of the diodes as they turn off. The diodes turn off as the ETO turns on, making the turn-on loss for the ETOs negligible in the presence of the di/dt snubber.

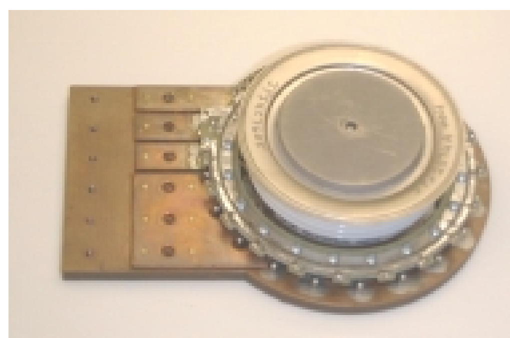


Figure 3-9. Picture of ETO1045HS Model.

System Configuration

Three-phase inverters are typical of high-power industry applications. A phase leg, composed of two switches and their anti-parallel diodes, is a standard building block for almost all high-power (voltage-fed) topologies. As the initial step of building an ETO application system, a simple configuration of the ETO system that makes use of a phase leg is shown in Figure 3-10. The boost topology was selected in order to achieve a high-voltage stress on the ETO without using a high-voltage power supply.

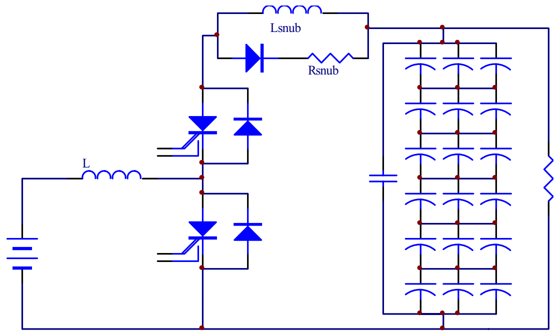


Figure 3-10. Boost Converter Based on a Standard Phase Leg.

System Construction

In order to build a high-power converter with an ETO, it was necessary to develop a phase leg (half-bridge) with two ETOs, two diodes, the associated gate drivers, and suitable heat sinks. The ETOs and the diodes are in assembled press-pack ("hockey-puck") packages, so mechanical clamping is necessary. The phase leg uses five liquid-cooled heat sinks so each device is cooled on both sides. Because the switches dissipate more power than the diodes, the two ETOs are separated from each other. Another requirement for the design of the phase leg is that the path length from each ETO to the opposite diode should be the same in order to equalize the voltage overshoot on the switches. The completed phase leg is shown with gate drivers in Figure 3-11.

Using a laminated bus and the ETO phase leg, a DC/DC boost converter (Figure 3-12) was built. It uses the bottom switch of the phase leg, and the top switch is always gated off.

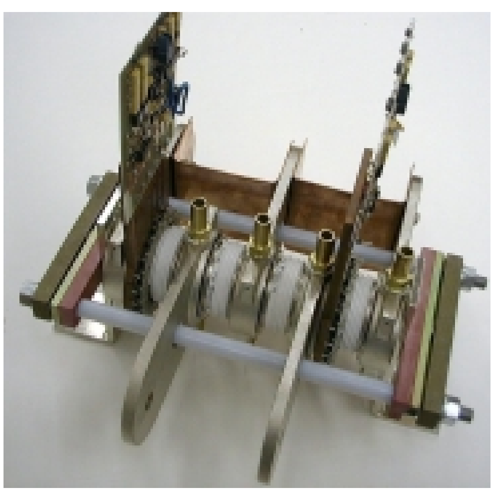


Figure 3-11. Photograph of Completed Phase Leg.

Figure 3-12. An Overall View of the Converter.

System Performance

The operating waveforms for the 100-kW test are shown in Figure 3-13. The stress on the ETO was 120-A switching current and 2000-Vdc (with 2250 -V peak spike). The overvoltage due to the di/dt snubber is about 250 V, which is reasonable compared to the DC link.

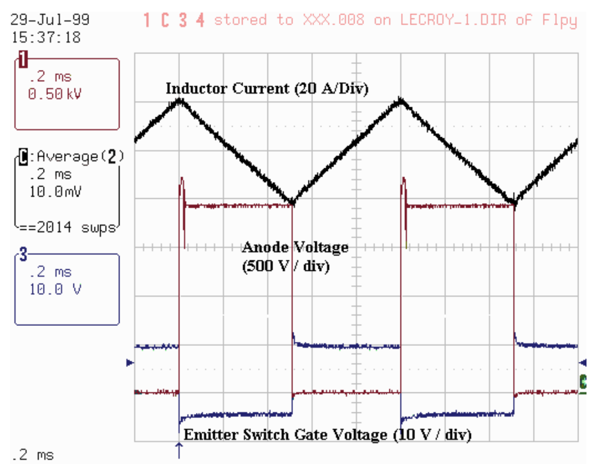


Figure 3-13. Waveforms of ETO System Running at 100 kW.

Major Accomplishments and Conclusion

An ETO-based 500-kW single-phase-leg converter has been built. It was tested at the 100-kW level, which is the power capability of the Center for Power Electronics Systems (CPES) lab, with a switch stress of 120 A/2250 V. The system exhibits a high operating frequency for thyristors at 1 kHz, good thermal management, and snubberless turn-off capability as well as ease of control. The gate driver features on-device overcurrent protection that has been verified on both the ETO1045 and the ETO4060. This protection acts when the device current has reached half of the maximum controllable current, thus preventing the current from rising out of the controllable range. This is allowed by the fast switching speed shown by the ETO in conjun c-tion with the di/dt limiting snubber that was developed in this phase of the project.

Future Plan

The next step for this converter is to increase the DC voltage to 3000 V. Increasing the current level without a large power supply will be accomplished by using reactive power transfer in an inductor-loaded full bridge. A three-phase multilevel inverter would be the typical application of a device such as the ETO, so the testing of such a system is the eventual goal of this converter. Additionally, soft switching techniques that can increase the operating frequency will be examined.

Development of Intelligent Controls and Control Strategies for Renewable Generation and Storage

Both the ESS and Photovoltaic Programs are inte r-ested in the development, design, and testing of an i m-proved, more versatile, and better integrated PCS. Power electronics and the supporting circuitry and software are critical to the eventual wide-scale use of renewables and energy storage technologies for many diverse applications. As documented in the recent SNL report, *Renewable Generation and Storage Project—Industry and Laboratory Recommendations* (SAND98-0591), the DOE ESS Program is embarking on a major initiative to address system integration and components of renewable generation and storage (RGS) systems. This project includes a competitive procurement for an industry partner to develop an intelligent system co n-troller and evaluate advanced control strategies for PCSs used in RGS applications, and will include tasks for design, applications analysis, fabrication, and co m-ponent and system testing.

Status

In FY99, the ESS Program gathered information from the energy storage and PV industries and noni n-dustry organizations such as the Florida Solar Energy Center and the New Mexico State University Techno l-ogy Development Institute to clearly define needs, d i-rections, and scope of an improved RGS controller project before initiating a request for information (RFI). The objective was to prepare a clear taxonomy of RGS controls, explore how these controls should be orga n-ized, and explore which functions are more natural to implement within subsystems and which functions are better suited to more advanced control principles.

A statement of work (SOW) for the controller pro j-ect was written. An RFI was sent to interested co n-tractors to review the SOW and solicit information on the nature and the extent of the demand for an improved RGS controller. The purpose of the RFI was to achieve industry “buy-in” on the controller concept. Once the RFI has been reviewed, and if the ESS determines that it is practical to proceed with this project, a request for quote (RFQ) will be issued in the first quarter of FY2000, with a contract award anticipated later in the year.

Evaluation

Valve-Regulated Lead-Acid Battery Evaluation

Controlled laboratory tests are the best method to determine battery capacity degradation rates and mechanisms. While batteries in field tests have the same problems, the often uncontrolled variability of the test environment slows the collection of data and makes it difficult to distinguish cause and effect.

Life cycle testing continued in FY99 at SNL on VRLA batteries, which were currently under test for utility applications, specifically the GNB ABSOLYTE II and ABSOLYTE IIP AGM batteries. The GNB batteries were deliverables from a develop ment contract with GNB. GNB is actively consulting on these tests.

ABSOLYTE IIP Testing

Status

Testing continued in FY99 using the H-test regime shown in Table 3-4. Testing halted at the end of FY98 at Cycle 610 on September 16, 1998, to diagnose erratic Cell 1 voltage readings. At this point, the capacity had decreased to 972 Ah, near the defined end of life (EOL) of 960 Ah. Cell 5 end of discharge (EOD) voltage, which had been low throughout life cycle testing, began to decline more rapidly through Cycles 500 through 600. Testing resumed on November 30, 1998, with nine diagnostic C/8 discharge cycles that used the H-charge regime and was performed during December 1998. Testing was suspended for the annual year-end plant shutdown, and was resumed on January 27, 1999. ABSOLYTE IIP capacities are shown in Figures 3-14 and 3-15, and EOD cell voltages are shown in Figure 3-16.

Table 3-4. ABSOLYTE IIP and ABSOLYTE II Test Regimes

H-Test Regime	
ABSOLYTE IIP	**ABSOLYTE II**
Discharge at 150 A to 14.0 V	Discharge at 150 A to 15.75 V
5-min rest	5-min rest
Charge at 300 A to 19.2 V	Charge at 300 A to 21.6 V
1-min rest	1-min rest
Charge at constant 19.2 V, with a maximum 300 A, tapering to 24 A or to 7% overcharge	Charge at constant 21.6 V, with a maximum 300 A, tapering to 24 A or to 7% overcharge
1-min rest	1-min rest
Charge at 24 A to 7% overcharge	Charge at 24 A to 7% overcharge
Wait 8 hr	Wait 8 hr

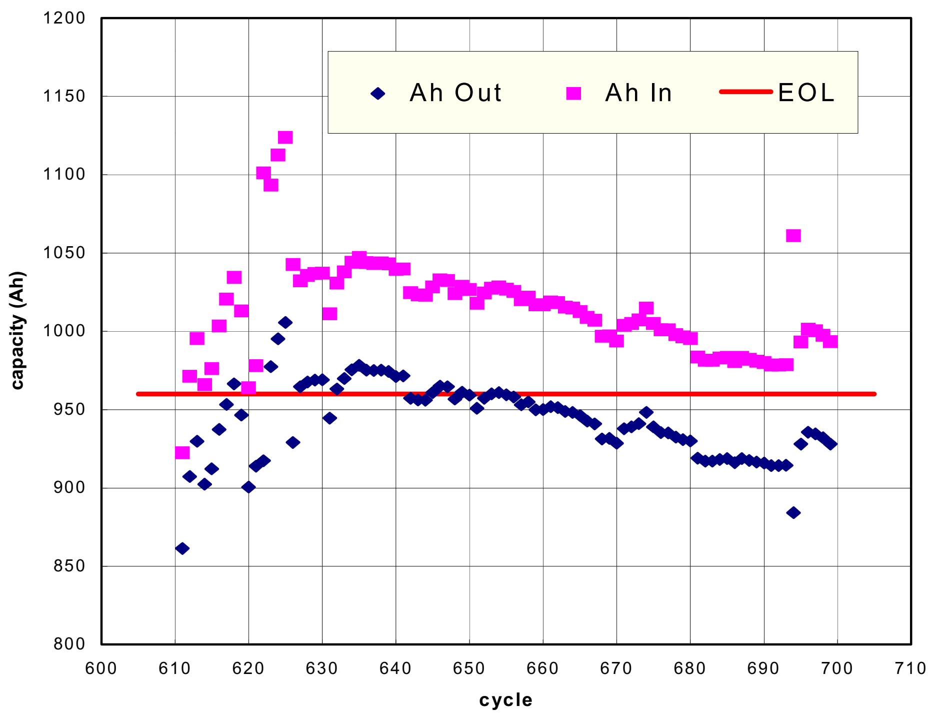


Figure 3-14. ABSOLYTE IIP Capacity vs. Cycle Number for FY99.

The erratic Cell 1 voltage problem was traced to an input voltage that exceeded common mode voltage limits on a tester input multiplex board. The board was changed to a relay-based type. Cycles 622–625 were performed using a 20% overcharge in place of the 7% overcharge of the H-test regime, which raised capacity to 1005 Ah at Cycle 625. Testing was suspended at this point for database upgrades. Testing was resumed on March 17, 1999, with capacities only slightly above the 960-Ah EOL level. The capacity continued to decline on succeeding cycles. By Cycle 693, capacity had d e-clined to 914 Ah, well past the end of life. An 18% boost overcharge was performed on Cycle 694, with slight improvement in capacity. Testing was halted on May 23, 1999, at Cycle 699, pending a decision on post-service-life tests.

A decision was made to attempt to recover some battery capacity. A boost charge of 1600-Ah input was performed on July 27, 1999, followed by two C/8 di s-charge capacity cycles. These three cycles (700, 701, and 702) are shown in Figure 3-17. The H-test regime was used on Cycles 701 and 702. Capacity improved slightly to 984 Ah on Cycle 701, but dropped to 938 Ah on Cycle 702.

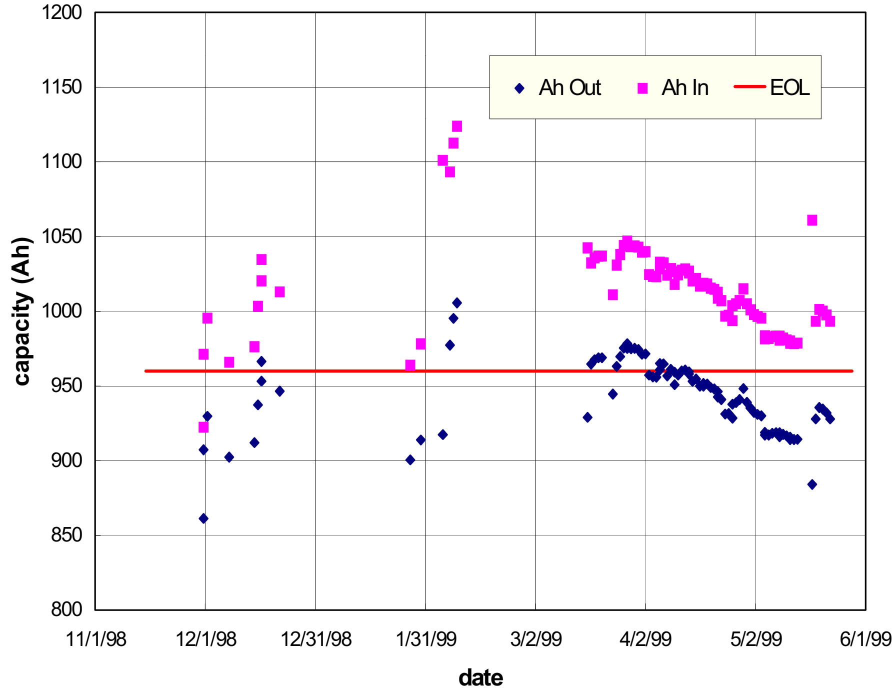


Figure 3-15. ABSOLYTE IIP Capacity vs. Date, Showing Periods of Open Circuit.

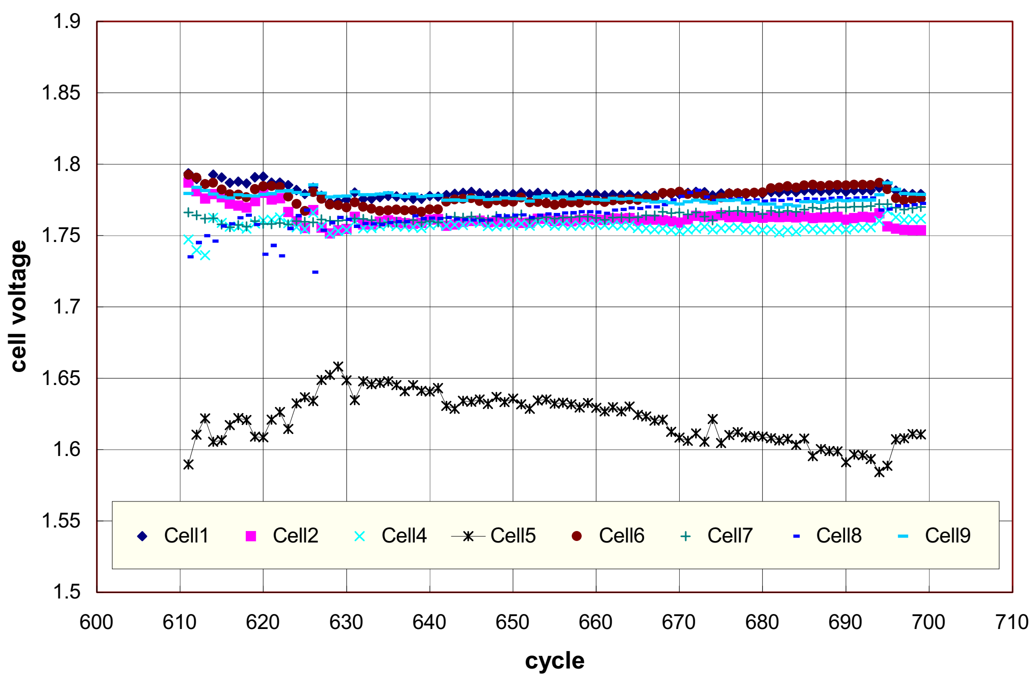


Figure 3-16. EOD Cell Voltages for the ABSOLYTE IIP—Cell 3 is Bypassed.

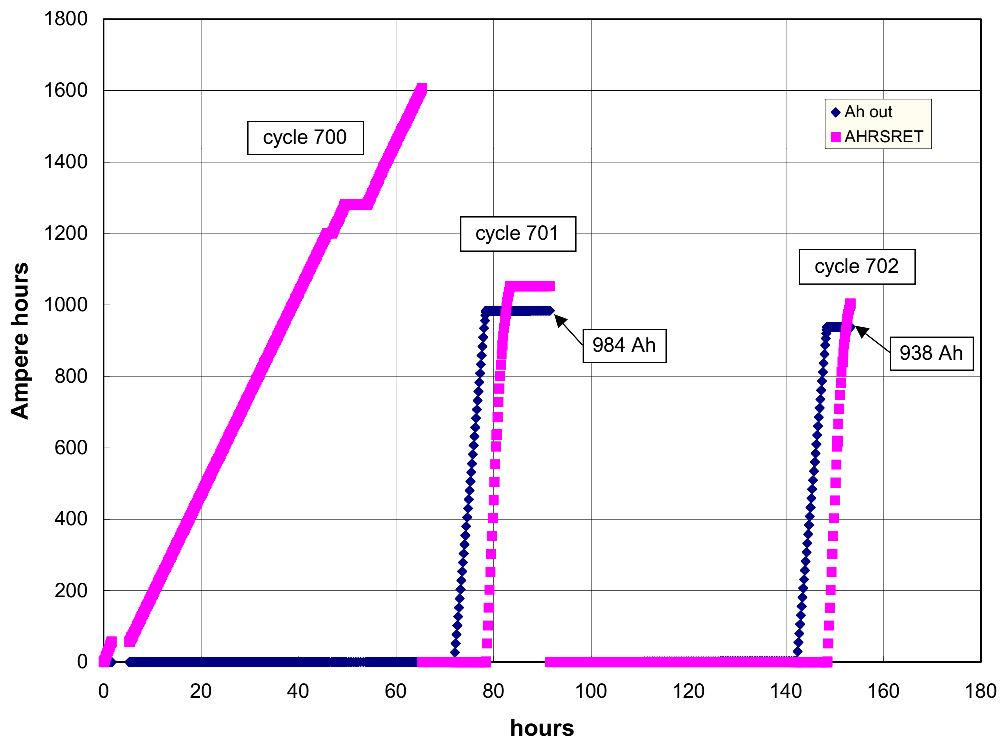


Figure 3-17. ABSOLYTE IIP Boost Charge and Capacity Cycles, After EOL Reached at Cycle 699.

GNB suggested that useful information on the cause of the decline of capacity could be derived from a refe r-ence electrode inserted into one cell. The vent was r e-moved from Cell 7, and a cadmium wire reference electrode was inserted for the discharge phase of Cycle 703. The battery was discharged at a constant 150 A to 14.0 V, producing 921 Ah capacity. Results of the voltage measurements are shown in Figure 3-18.

The results were sent to GNB, which replied that the cell appeared to be positive-limited, but that the negative was starting to polarize. GNB suggested that this is typical of acid starvation, and that the cell may be sulfated. This polarization could also be associated with dryout. It was suggested that a very aggressive charge profile be tried to determine if some capacity could be recovered. An aggressive charge program will be planned and tried in the first quarter of FY 2000.

ABSOLYTE II Testing

Status

Life cycle testing of the ABSOLYTE II battery continued in the latter half of FY98 and into FY99, u s-ing the ABSOLYTE II H-test regime shown in Table 3-4. This test regime is identical to the ABSOLYTE IIP test regime in Table 3-4 except that the charge and discharge voltages of the ABSOLYTE IIP are adjusted for eight cells and those of the ABSOLYTE II are a d-justed for nine cells. A discharge current of 150 A was used for the ABSOLYTE II through most of the life testing instead of a C/8 current of 130 A, so direct com-parisons could be made with the A BSOLYTE IIP.

The capacity had been steadily decreasing, as r e-ported in the ESS Program Report for FY98, SAND98-0883. As was also reported, there were ambient te m-perature fluctuations in the building where the ABSOLYTE II was being tested that caused fluctu a-tions in measured capacity and contributed to tester malfunctions. In October 1998, the testing was halted for air conditioning and tester repairs. Twenty-three cycles (376–398) using the H-test regime were run during December to evaluate tester modifications. The battery was then on open circuit from December 22, 1998, to February 13, 1999, when testing resumed. Capacity vs. cycle number is shown in Figure 3-19, and capacity versus date is shown in Figure 3-20.

Cell 4 EOD voltage, which had been consistently below that of other cells, began to decline sharply shortly before the testing was halted in October 1998 (Figure 3-21) and stayed low. Capacity also declined, reaching the EOL value of 832 Ah at Cycle 440. At Cycle 441, a boost overcharge of 148% returned 1232 Ah was performed, with a slight improvement in

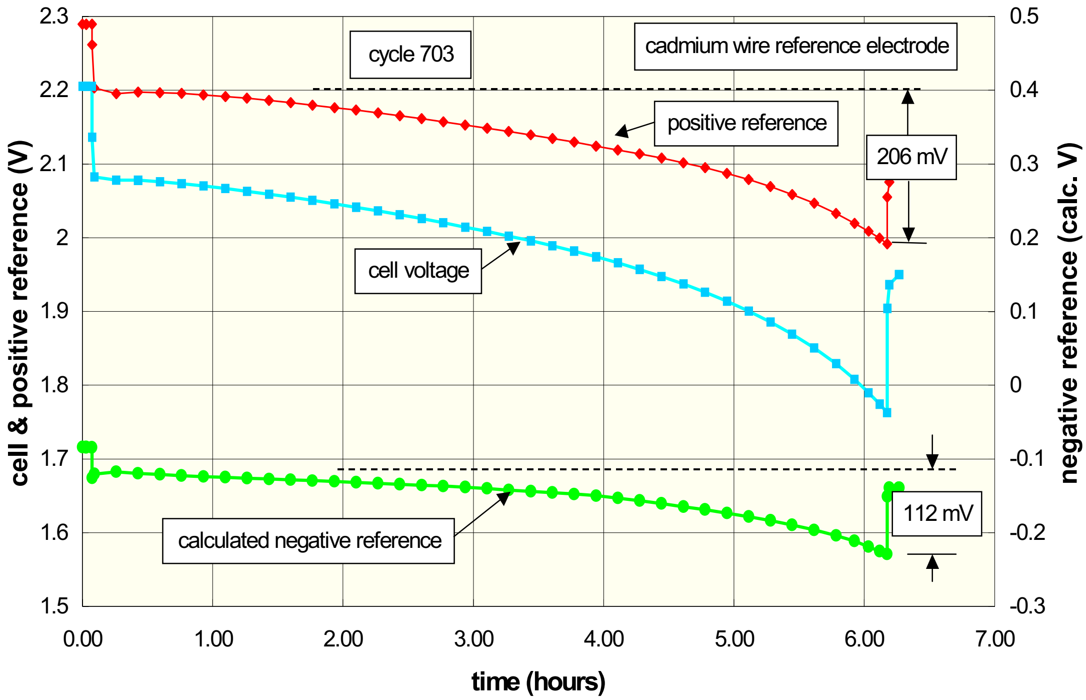


Figure 3-18. Voltages Measured and Calculated Using a Cadmium Reference Electrode in Cell 7 of the ABSOLYTE IIP.

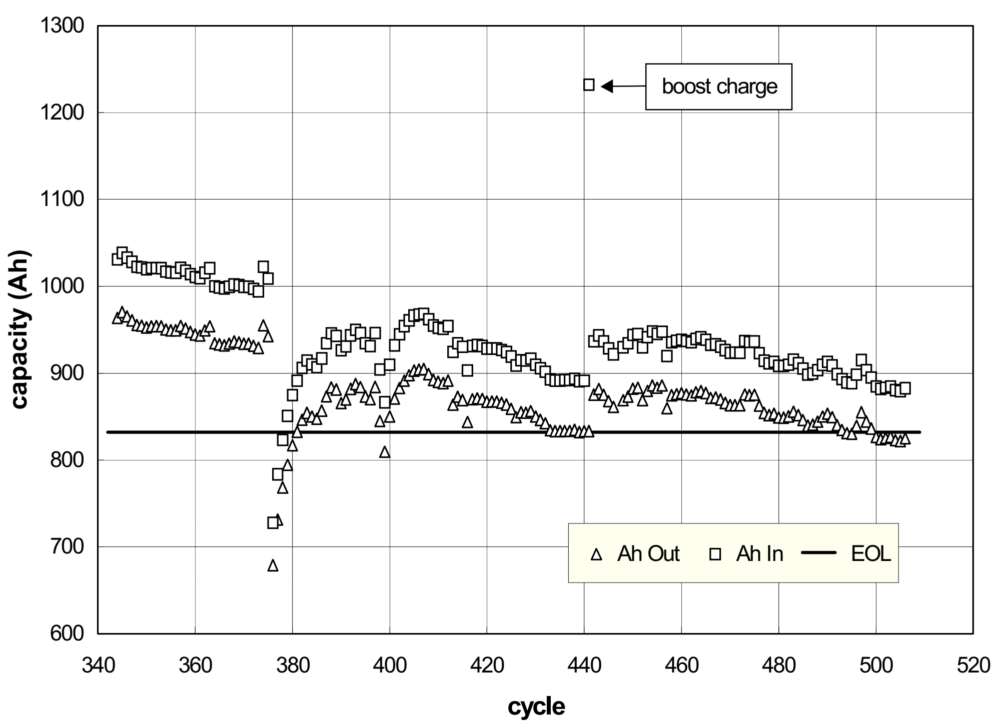


Figure 3-19. ABSOLYTE II Capacity vs. Cycle Number for FY99.

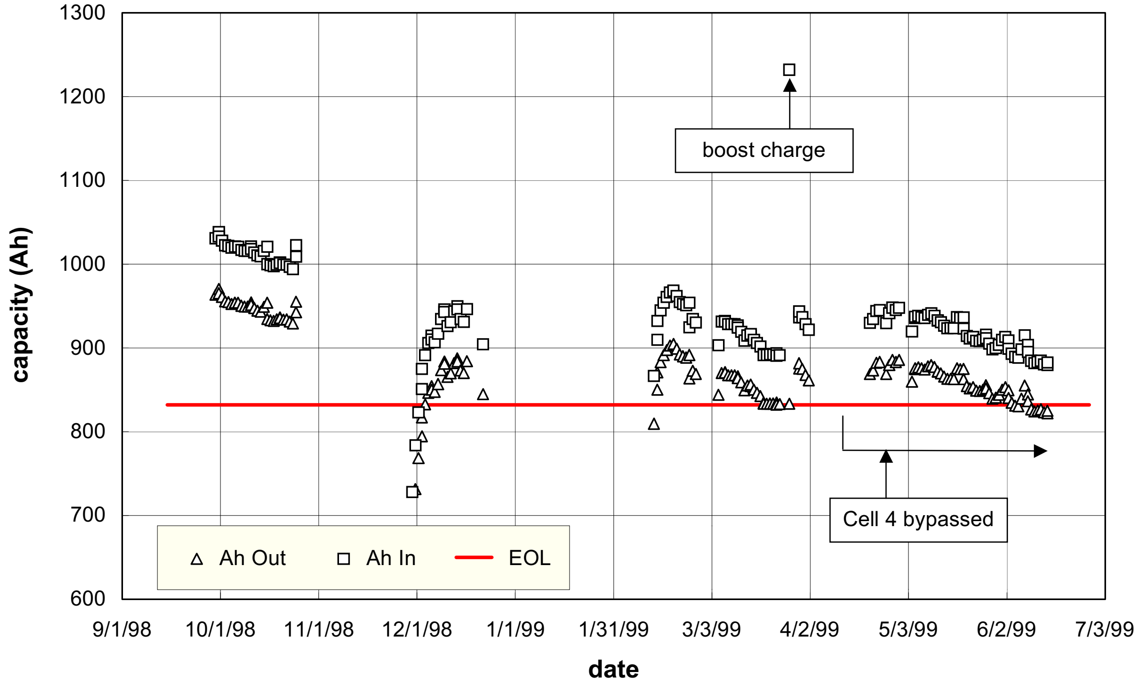


Figure 3-20. ABSOLYTE II Capacity vs. Date, Showing Periods of Open Circuit.

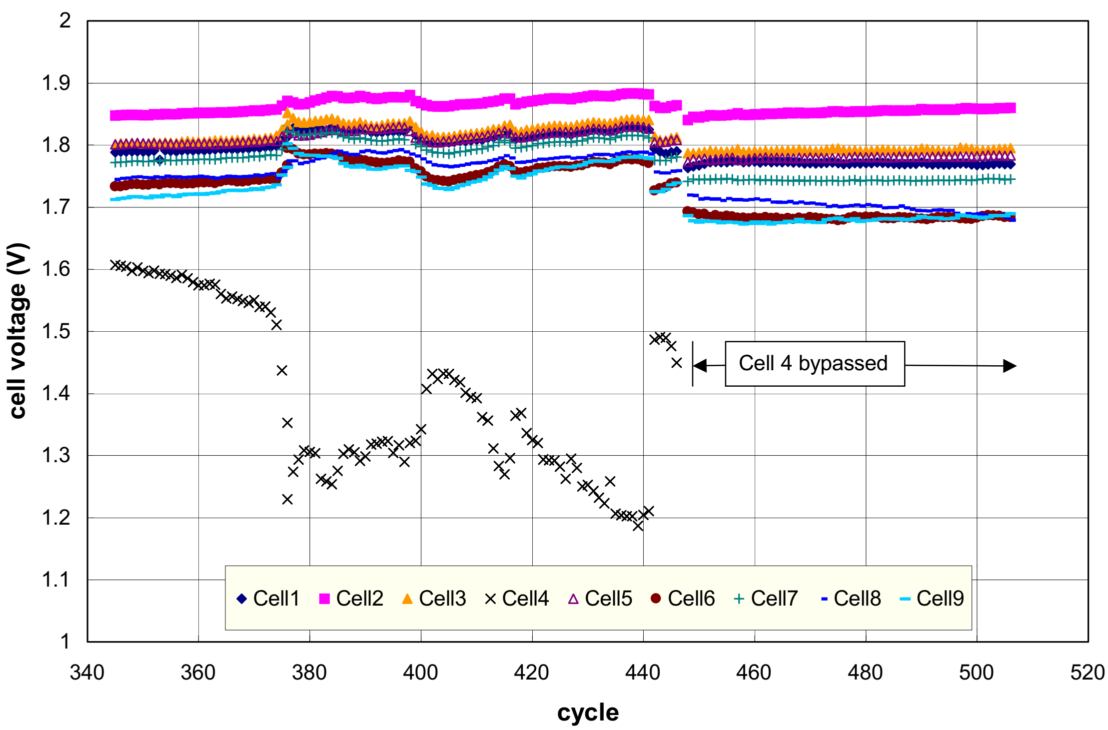


Figure 3-21. EOD Cell Voltages for the ABSOLYTE II. Cell 4 was Bypassed after Cycle 446.

capacity and in Cell 4 EOD voltage on subsequent c y-cles. Cell 4 EOD voltage was still significantly lower than other cells, and at Cycle 446 Cell 4 was bypassed. The ABSOLYTE II H-test regime was modified to be appropriate for eight cells, making it identical to the ABSOLYTE IIP H-test regime.

Life cycle tests continued with declining battery capacity. By Cycle 506 (June 15, 1999), capacity was consistently below the 832 Ah that corresponded to 80% of rated capacity, and testing was halted. The battery was on open circuit for the remainder of FY99. A decision will be made on further testing or dispos i-tion of the battery.

Yuasa Laboratory Testing for Hybrid Environment

In early 1998, a 24-Vdc string of 12 Yuasa Exide, Dynacel DGX tubular gel VRLA cells were received at SNL. A test plan was developed to test these special cycling batteries in a laboratory. The test program emulated the off-grid hybrid operational environment and was run in parallel with the actual field testing of the DGX batteries at the APS STAR Center Hybrid Test Facility in Tempe, Arizona. This test program provided a data point to compare to the Dynacel DGX battery at STAR, which is being tested in an actual h y-brid operating environment. The battery is exposed to a cycling regime denoted as a complete capacity cycle (CCC), in which the battery is operated above 50% and below 80% SOC for extended periods of time. It is currently believed that the tubular gel battery can ope r-ate at intermediate states of charge for extended periods of time with little if any sulfation and no stratification effects. If this is true, the use of this technology can possibly lead to the development of an optimal opera t-ing strategy for off-grid RGS applications. Cycle tes t-ing began in October 1998 and continued throughout FY99. All testing was done in-house at SNL.

Status

The first cycle of FY99 (CCC 1) ended on October 24, 1998. The nameplate rating for the DGX battery is 405 Ah (all charges and discharges were co n-ducted at a 5-hour rate). At the end of CCC 1, the c a-pacity test indicated that the battery was at 88% of its rated capacity. At the end of CCC 2, the battery capa c-ity had risen to 91%. From that point on, capacity d e-clined for the next six CCCs. During the first half of the fiscal year, the battery exhibited a severe drop in c a-pacity, to a rating of 77% by CCC 8. At this time, the battery was operated for about 500 cycles at 30% c a-pacity.

As indicated in Figure 3-22 for CCCs 3 through 8, string capacity fell by more than 10% over a period of about six months. Several meetings and telephone co n-ferences were conducted during the period in an attempt to determine why the DGX cells were exhibiting pr e-mature capacity loss (PCL).

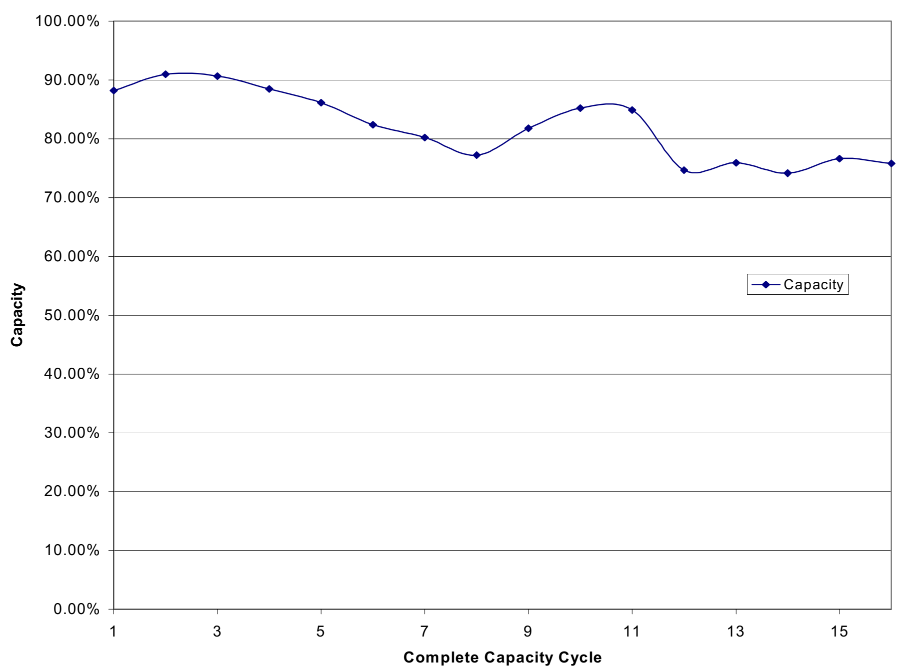


Figure 3-22. Yuasa Exide DGX Capacity History.

Testing of the DGX battery was temporarily halted in late February following CCC 8 as test results indicated that the battery was not being properly recharged following each complete cycle. In Cycle 509, which was completed in mid-February, capacity had fallen to 77% of the nameplate rating after completing the equivalent of 163 cycles at 100% DOD. A meeting was held in mid-February with Yuasa engineers to review the test results. A second meeting was held in mid-March at the Yuasa offices in Reading, Pennsylvania. EECI represented SNL at the meeting. The findings from the meeting were that the battery had not been charged correctly while charging from 50 to 80% SOC. It was recommended that the charge voltage be raised to 2.40 Vpc. This increase in charge voltage appeared to solve the problem, and over the next several CCCs capacity increased to near 86% rated capacity.

Following CCC 11, however, the DGX cells exhibited a severe drop in capacity after the completion of approximately 380 operational cycles. During the period of June to July following CCC 12, string capacity fell dramatically by more than 10%. Several meetings and telephone conferences were conducted during this period in an attempt to determine why the cells were again exhibiting PCL after the recovery in late February. In early June, Yuasa engineers provided a new charge algorithm. The new algorithm proposed a constant voltage, constant current (CVCI) charge regime, which is considerably more aggressive than the original constant voltage charge algorithm. In the constant current charge, the cell voltage was allowed to rise to 2.55 Vpc while the current was limited to 12 A. As noted in Figure 3-19, capacity did not continue to fall but appears to stabilize around the 75% capacity point. However, according to the test plan, the test was to be terminated when the capacity of the battery fell below 80% rated capacity. At the end of FY99, the test was terminated after completing 1,082 operational cycles at 50 to 80% capacity.

Table 3-5 shows the complete history of the test program. The battery was expected to deliver 800 cycles at 100% DOD for an expected energy life of 324,000 Ah at the 5-hour rate of the tests. Using accumulated ampere hours delivered (130,603 Ah), the battery was at 75% nominal nameplate rated capacity after having delivered 40% of its rated life in ampere hours. Another interesting item in Table 3-5 is found in the percent overcharge column. It appears there was no significant overcharge delivered (accumulated Ah returned/removed), which was not the case. During the 30% charge and discharge cycles, the exact

Table 3-5. Yuasa Exide Dynacell DGX Life History Table

CCC	30% Cycles	Nominal Capacity	Capacity	Ah Removed	Accumulated Amp Hours		
					Removed	Returned	Percent Overcharge
1	64	357.18	88.19%	283.45	8,834	8,933	101.12%
2	128	368.40	90.96%	309.36	16,999	17,158	100.94%
3	191	367.25	90.68%	300.52	25,150	25,359	100.83%
4	261	358.40	88.49%	293.37	34,109	34,378	100.79%
5	323	348.90	86.15%	289.21	42,118	42,430	100.74%
6	385	333.73	82.40%	265.70	50,086	50,445	100.72%
7	447	324.93	80.23%	268.31	58,048	58,443	100.68%
8	509	312.72	77.21%	251.47	65,979	66,412	100.66%
9	573	331.23	81.79%	296.03	74,287	74,795	100.68%
10	636	345.20	85.23%	271.52	82,261	82,833	100.70%
11	698	343.93	84.92%	275.02	90,245	90,894	100.72%
12	763	302.48	74.69%	265.22	98,177	98,825	100.66%
13	826	307.57	75.94%	266.85	106,459	107,268	100.76%
14	889	300.33	74.16%	260.28	114,398	115,276	100.77%
15	952	310.39	76.64%	254.79	122,339	123,262	100.75%
16	1,017	306.93	75.79%	254.75	130,603	131,706	100.84%

number of ampere hours removed were returned during the charge portion of each 30% cycle. This strategy is very reasonable as the battery charge acceptance efficiency is nearly 100% over this operating regime. Further analysis yielded information that verified that the proper manufacturer's recommended overcharge of 10% was applied during the normal full recharge periods, which occurred every 60 cycles at 80 to 50%. Following each 110% complete charge, the battery was fully equalized, again using the manufacturer's suggested procedure for equalization.

The question as to why the battery did not recover under the aggressive CVCI charge program needed to be answered. The most plausible explanation for this may be that the battery had been severely, if not permanently, damaged during the preceeding 12 CCCs and required even more controlled overcharge to recover the cells. Another question that needed to be answered was why the cells were experiencing PCL. After many discussions with Yuasa battery engineers, it appeared that another mechanism besides the typical sulfation buildup was driving the PCL. Yuasa engineers will attempt to determine the characteristics of this PCL mechanism. In early FY2000, the SNL DGX battery will be dismantled and returned to Yuasa for further testing and tear-down.

Intermediate State-of-Charge Testing

The ISOC test project was initiated in early FY98, and testing of batteries from several participating manufacturers began in the first quarter of FY99 at the SNL test laboratories. Two VRLA gel electrolyte batteries and one AGM battery from three manufacturers were tested as single units and in a 60-V string to determine whether the batteries can operate in an ISOC environment without damage. The ISOC environment allows for better energy management in off-grid applications by not requiring a full 100% recharge following discharge operations. During FY99, the test project required internal technical support to ensure continued and reliable operation of the test equipment and data management system. No external contracts were needed to support this project.

Because of initial agreements with the battery manufacturers who provided batteries for this test program, information on test results are reported for Batteries A, B, and C with no specific reference to the manufacturer or battery model. Following completion of the test program, information for test results from specific manufacturers and models may be made available if manufacturers give their permission to release the information.

Status

Testing continued throughout FY99. Tables 3-6 through 3-8 summarize the results through the end of the period. Batteries A and B are flat-plate gel technology, and Battery C is an AGM. All are exposed to the ISOC operational regime where the battery is operated between 50% and 80% SOC with periodic capacity tests followed by full charges and equalization charges that occur every 60 ISOC cycles. Following each of the three tables are discussions of the particulars of each of the three batteries. Columns 1 and 2 (in Tables 3-6 through 3-8) give the data on the 12-V modules under test. Column 3 in each of the tables gives the data on the 60-V string consisting of five modules.

Because of the way energy is removed from batteries in a hybrid cycling environment, the term "cycle" is somewhat misleading when one considers what really constitutes a cycle. Depth and rate of discharge both influence battery cycling performance. However, all batteries are designed to deliver a fixed number of ampere hours based on the amount of active material that is manufactured into a battery. For fixed cycling applications where loads and depth of discharge are always the same, a cycle is obvious. On the other hand, when loads and depth of discharge vary, defining a cycle is not so obvious. Consequently, the use of ampere hours delivered is a more accurate definition of battery performance in a variable cycle environment. All capacity measurements reported for ISOC testing are based on the total expected ampere hours that are available from the battery given the number of 100% cycles at the five-hour rate. Battery A is rated to deliver 20,700 Ah over a period of 300 cycles at the five-hour rate. Battery B is rated to deliver 24,150 Ah over a period of 300 cycles at the five-hour rate. Battery C is rated to deliver 28,000 Ah over a period of 400 cycles at the five-hour rate. All batteries undergoing ISOC testing have exceeded their rated cycle life as of the end of the FY.

Table 3-6. Module and String Data for Batteries on Test–Type A

Battery A	A-1 12-V Module	A-2 12-V Module	A-3 60-V String
ISOC Cycle Sets	16	16	16
Cycles Completed	1,012	1,010	1,009
Rated Capacity Ah	69	69	69
Current Capacity	53.7	57.6	42.7
% Rated Capacity	77.8	83.5	61.9
Equivalent 100% Cycles Completed	322	314	312
Equivalent 30% Cycles Completed	1,072	1,046	1,041

Battery A was not rated for a specific number of cycles in the manufacturer's specification sheet. Typically, this type of battery is expected capacities of 300 complete 100% cycles. Nominal capacity has fallen below the 75% capacity target for A-1 and A-3; however, the batteries continue to support their loads with no apparent effects from the reduced capacity. The batteries will continue on test for several more CCCs in FY2000 in order to determine how the batteries behave in a cycling environment as they approach the end of their functional life.

Table 3-7. Module and String Data for Batteries on Test–Type B

Battery B	B-1 12-V Module	B-2 12-V Module	B-3 60-V String
ISOC Cycle Sets	16	16	16
Cycles Completed	1,012	1,010	1,009
Rated Capacity Ah	69	69	69
Current Capacity	53.7	57.6	42.7
% Rated Capacity	77.8	83.5	61.9
Equivalent 100% Cycles Completed	322	314	312
Equivalent 30% Cycles Completed	1,072	1,046	1,041

Battery B is rated for 300 cycles at 100% DOD in the manufacturer's specification sheet. Nominal capacity has held in the 80% range for Module 2 while Module 1 and the string capacity has fallen below the test capacity termination threshold of 75%. Testing will be terminated for all three units in early FY2000. Note that all three B batteries have greatly exceeded the manufacturer's 100% cycle projection of 300 cycles and all units remain functional despite their decline in measured capacity.

Table 3-8. Module and String Data for Batteries on Test–Type C

Battery C	C-1 12-V Module	C-2 12-V Module	C-3 60-V String
ISOC Cycle Sets	20	20	20
Cycles Completed	1,280	1,269	1,274
Rated Capacity Ah	80.5	80.5	80.8
Current Capacity	57.2	64.5	49.5
% Rated Capacity	72	81	62
Equivalent 100% Cycles Completed	412	410	382
Equivalent 30% Cycles Completed	1,374	1,312	1,314

Battery C is rated for 400 cycles at 100% in the manufacturer's specification sheet. Nominal capacity has held in the 80 to 85% range for the last several CCCs. There has been one module failure in the string (C-3), which resulted in the removal of the defective module and the resumption of cycling with only four modules in the string. All units are near or have exceeded the manufacturer's life cycle rating and all units are holding up well. Testing will continue until capacity falls below the 75% rated capacity.

It is anticipated that the ISOC test program will meet its expected goals and testing will be terminated during the first quarter of FY2000. An interesting observation as to how capacity declines and how to improve management strategies for a cycling environment will be published as a SAND report sometime in FY2000. Details of the performance of each battery will also be published in FY2000. If permission is granted by the manufacturers, details of each model and part numbers will be included in the report.

System Evaluation of a 200-kWh Zinc/Bromine Battery at "The Barns"

In FY97, after completing a competitive procurement process, the ESS Program initiated a contract with Powercell Corporation to perform in-house tests on Powercell's Zinc-Flow™ battery. The project was expanded in FY99 to include the field characterization of 100-kWh units that Powercell calls the PowerBlock. Two 100-kWh PowerBlocks were built and will be field tested at "The Barns," a community theatre at Franklin Park in Loudon County, Virginia. This project will entail monitoring both battery performance and energy use/generation of all the major system components.

Status

The location of the field test was negotiated early in FY99. The size of the battery was increased to 200 kWh for this application. It will be charged by a solar array and grid power. Its primary purpose is to store solar energy generated in the day for use at night.

The electrical design for the building was completed in the third quarter. The design allows for optimum use of the BESS. A plan was developed based on this design to measure energy use/generation of the major components. The plan enables the project team to perform energy balances for the entire system. A draft plan for implementation (Figure 3-23) was completed in the third quarter.

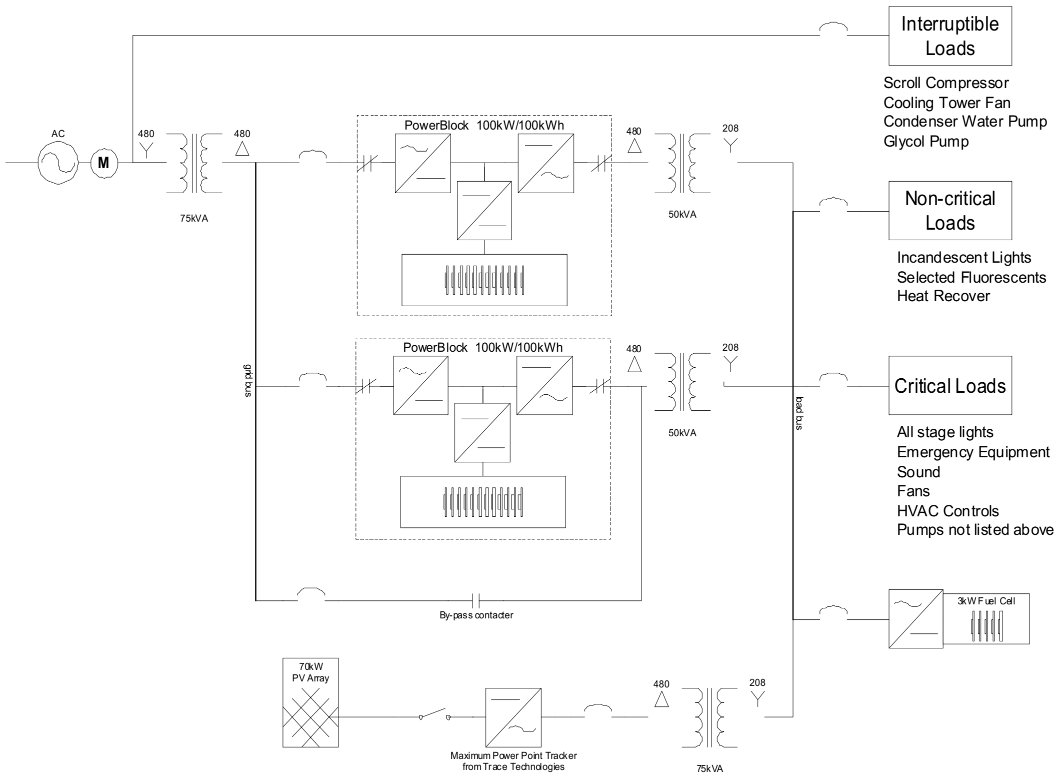


Figure 3-23. The Barns Implementation Plan.

The Barns theatre is intended to be a net producer of green power, with a 200-kWh energy storage system and a 70-kW PV array. PowerBlock performance data and its response to grid failure are presented in Figures 3-24 and 3-25. Some of the most significant features of the PowerBlock unit are:

- four-quadrant control system,
- zero switching time backup,
- small footprint,
- mimimum maintenance,
- environmentally safe and benign.

The PowerBlock will function to eliminate the following events:

- Sags, surges, and spikes
- Noise and harmonic distortions
- Under- and overvoltages
- Interruptions and outages

The unit also functions to reduce the following:

- Demand charges
- VAR charges
- Generator maintenance costs

The state-of-the-art power electronics unit (Figure 3-26) for the system is IGBT based, and has high eff i-ciency, four-quad operation, double conversion, fiber-optic controls, and a water cooling system.

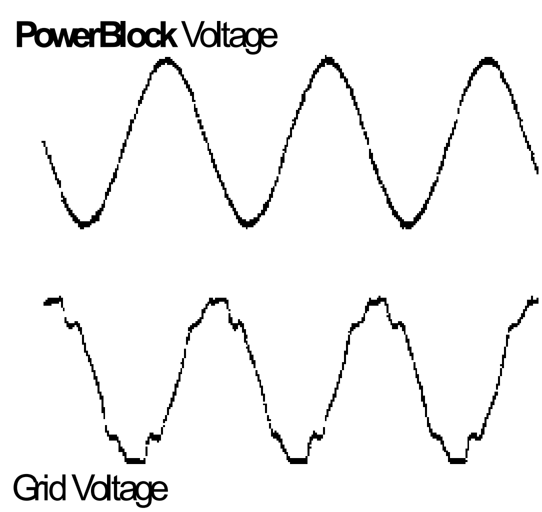


Figure 3-24. PowerBlock Performance Data.

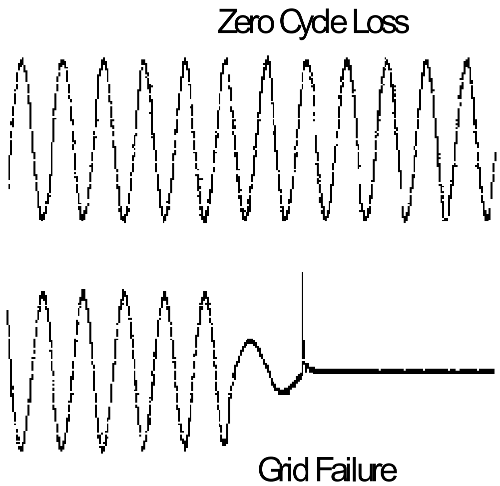


Figure 3-25. PowerBlock's Response to Grid Failure.

Figure 3-26. PowerBlock State-of-the-Art Power Electronics.

4. Analysis

Introduction

The analytical tasks being performed in FY99 derive from studies conducted in past years. The Analysis program element contains two subelements: (1) system studies and (2) technology assessments.

A system study is an initial screening study performed to identify and evaluate the potential applications and benefits of energy storage. This screening study establishes a rough estimate of the benefit-to-cost ratio of storage using a limited examination of user-specific operating and financial data as a basis.

Technology assessments evaluate the state of the art of storage and other relevant devices. These evaluations include the identification of appropriate technologies, a literature search, discussions with suppliers, and modeling. The ultimate objectives of these assessments are to characterize technologies to determine their suitability for stationary applications and to define research needed to successfully develop and field advanced technologies in working systems.

System Studies

Opportunities Analysis—Phase II

The Opportunities Analysis was conceptualized in FY94 as a two-phase project. Phase II of the project, started in FY98, is an extension of Phase I of the study performed earlier by the ESS Program. In a preliminary assessment of national benefits, SNL estimated that generation and transmission applications of storage could represent $17.2B in national benefits. In Phase I of the Opportunities Analysis, the T&D benefits were found to be significantly higher than previous estimates.

Phase II of the study included a refinement of the technical and economic understanding of the role of energy storage in the utility industry. Increased understanding will help promote appropriate development and more rapid commercialization of utility ESSs. The current information is insufficient to estimate market size with a high degree of confidence, especially from a system supplier's perspective. Activity in Phase II primarily focused on the need to characterize the near- and long-term utility application requirements for energy storage.

Status

The first meeting of Phase II of the Opportunities Analysis study was held November 1 and 2, 1998, in Santa Fe, New Mexico. The meeting was attended by 15 representatives from the storage and related industries, several Sandians, and staff from Energetics. The meeting focused on specifying application requirements for stationary energy storage and categorizing them according to a structure meaningful to electricity suppliers and consumers, and reaching consensus on clear terminology.

On April 22 and 23, 1999, representatives from DOE/SNL and Energetics and stakeholders from various parts of the energy storage, power electronics, and electric power industries met to conduct Meeting II.

The goals of the meeting were to:

1. Reassess the value of applications for energy storage in a competitive electric power industry;
2. Refine definitions of application requirements for ESSs;
3. Identify the best applications for specific ESS technologies;

Participants in the meeting included representatives from the following stakeholder groups:

- Electric-service providers
  - Enron Energy Services,
  - Northern States Power,
  - Public Service of New Mexico,
  - Southern Company,
- Technology developers
  - Active Power,
  - Argo Tech,
  - American Superconductor,
  - ESA,
  - GNB Industrial Technologies,
  - Omnion Power Engineering,
  - ZBB,
- Industry and technology experts
  - U.S. DOE,
  - Energetics,
  - ILZRO, and
  - SNL.

Participants reviewed the requirements for each of the following applications and modified some of the application names to better reflect the nature of the applications. The following application names emerged from this review:

- Rapid reserve,
- Area control and frequency responsive reserve,
- Commodity storage,
- Transmission system stability,
- Transmission voltage regulation,
- T&D facility deferral,
- Distribution facility deferral,
- Renewable energy management,
- Customer energy management, and
- Power quality and reliability.

The group of industry experts who participated in the Phase II analysis used the perceived need for the application across the nation and the potential technical and economic benefits for utilities as criteria to evaluate the applications. From this process emerged the definitions shown in Table 4-1 for ten individual applications of energy storage that are in general demand and have high value with electric power producers and their customers. Table 4-1 also shows an organization of the applications under headings of Generation, T&D, and Customer. Although utility functions of generation, T&D, and customer service now generally occur in separate business units, the organization of the applications under those headings does not signify that a storage system could or should serve only one application or application type. In fact, a storage system is most valuable when it performs multiple functions in more than one of these groups of applications.

Regulatory, operational, and economic influences create technical requirements for each electric power application of energy storage. The industry experts who participated in this study identified the application requirements shown in Table 4-2 as the most significant to electric power applications: power; duration of discharge; AC system voltage; floor-space requirements; portability; and the type, number, and distribution of duty cycles. The characteristics of the operating environment are also important to technical requirements by the application on an ESS.

The information in Table 4-3 summarizes the requirements of each of the applications.

The technical attributes of the various storage technologies considered in this study are compatible with some electric power applications and incompatible with others. Table 4-4 identifies the level of compatibility between each of the ten applications and the storage technologies under consideration. The following information was included when the compatibility ratings were being considered: the technologies' capabilities in the near- and mid-term (as presented by participants in this study who develop the technologies and as reviewed by the other participating technologists); the information in the preceding descriptions of the storage technologies; and technical and nontechnical alternatives and the application requirements presented in preceding tables. Table 4-4 does not address the disparate state of development and experience of the storage technologies; nor does it address the cost-competitiveness of the technologies in the various applications. For example, flooded lead-acid and VRLA batteries have a D rating for area control and frequency responsive reserve, while composite rotors have an L rating. These ratings indicate that flooded lead-acid batteries can definitely serve the application and that composite flywheels are likely to be able to serve the application in the future. These ratings are based on the fact that lead-acid technology has already successfully served the application, and composite flywheel developers believe that their technology will also successfully serve the application. The ratings do not reflect which technology will address the application requirements in a more cost-effective manner when they are at the same level of technical maturity and experience.

Participants also reviewed the information on technologies with which storage will have to compete with in serving these applications. From this review, the group identified a need to characterize competing technologies to ensure that the list of technologies is complete, that the technology capabilities are accurately represented, and that the power and energy costs associated with the competing technologies are current. In particular, participants agreed that an evaluation of the market share for storage would require refined cost breakdowns for each competing technology. A need for identifying competitive drivers for each of the applications was expressed.

Another result of the study was that research is needed on the interface and balance of system issues associated with the differences in the storage media. For example, VRLA batteries require tightly controlled charge management to achieve reasonable service life; FES needs to stabilize a variable signal from its MG before serving a load. Participants also identified the various stages of development that each type of storage system has achieved to date. For example, flooded lead-acid batteries are fully mature and commercially available, and are integrated with the PCS. VRLA is commercially available and is integrated with the PCS

Table 4-1. Definitions and Categories of Electric Power Applications of ESSs

Definition	Category
Rapid Reserve Generation capacity that a utility holds in reserve to meet National Energy Reliability Council (NERC) Policy 10* requirements to prevent interruption of service to customers in the event of a failure of an operating generating station. **Area Control and Frequency Responsive Reserve** The ability for grid-connected utilities to prevent unplanned transfer of power between themselves and neighboring utilities (area control) and the ability of isolated utilities to instantaneously respond to frequency deviations (frequency responsive reserve). Both applications stem from NERC Policy 10 requirements. **Commodity Storage** Storage of inexpensive off-peak power for dispatch during relatively expensive on-peak hours. In this report, Strategic Storage for Systems Management refers to applications that require less than four hours of storage.	**Generation**
Transmission System Stability Ability to keep all components on a transmission line in sync with each other and prevent system collapse. **Transmission Voltage Regulation** Ability to maintain the voltages at the generation and load ends of a transmission line within 5 percent of each other. **Transmission Facility Deferral** Ability of a utility to postpone installation of new transmission lines and transformers by supplementing the existing facilities with another resource. **Distribution Facility Deferral** Ability of a utility to postpone installation of new distribution lines and transformers by supplementing the existing facilities with another resource.	**Transmission and Distribution**
Renewable Energy Management Applications through which renewable power is available during peak utility demand (Coincident Peak) and available at a consistent level. **Customer Energy Management** Dispatch of energy stored during off-peak or low-cost times to manage demand on utility-sourced power. **Power Quality and Reliability** Ability to prevent voltage spikes, voltage sags, and power outages that last for a few cycles (less than one second) to minutes from causing data and production loss for customers with demands of less than 1 MW.	**Customer Service**

* NERC Policy 10, Draft 3, is available for downloading through Word 97 and A crobat at http://www.nerc.com/~oc/standards/

Table 4-2. Definitions for Applications Requirements

Power requirements are measured in kilo- or megawatts (kW or MW) and kilo- or mega-vars (kVAR or MVAR) if the application requires reactive power: Power requirements determine the capacity of the PCS and can influence the size of the system via the power-to-energy ratio. The ESS must be rated so that power drain does not reduce its cycle life. Power requirements impact the size and cost of the ESS, the support structure, and the building. High power levels increase the cost of the control and power-handling equipment. Electric arc furnaces, cranes, welding machines, rolling mills, and other induction motors typically have large and/or widely fluctuating needs for reactive power. Inadequate reactive power supply can cause production or operational disturbances and reduce the life of manufacturing equipment. Utilities experience higher impedance and reduced capacity on T&D lines that experience reactive loading. Therefore, power providers charge a kVA demand charge to compensate for this cost. To avoid this charge, industrial facilities often try to supply reactive power on site using generators, capacitors, synchronous motors, and other technologies.

Duration of discharge, measured in minutes (min), determines the energy requirements for the storage system as measured in kilo- or megawatt-hours (kWh or MWh) or as measured by the hours (hr) of storage: Energy is the amount of power delivered over a period of time. Therefore, the longer the discharge duration at any power, the greater the energy that the storage system must be able to deliver. Energy requirements typically determine the size of the system. Consideration must be given to effects of discharge depth on the service life of the system. Higher energy requirements result in increases in the size and cost of the shelter and storage structural requirements.

AC system voltage requirements as measured by the root-mean-square of the load's requirement for kilovolts (kV_{ac}): The AC system voltage determines the size and cost of the transformer used between the PCS and the AC source and load. Voltage requirements also influence the gauge and cost of cabling for the system as lower voltages to reduce transformer costs cause higher currents and increased cable size and cost.

Floor space or footprint requirements, as measured in square feet of area, that the ESS occupied (ft^2): As implied above, the application requirements influence physical size, and the physical size affects the cost of the entire system. For many applications, and for some utilities, space availability is very significant in the selection and cost of storage systems.

Portability requirements, as measured by relative difficulty or cost of transporting the ESS: Some applications are temporary in nature; therefore, the ability to transfer a storage system from site to site can significantly increase its overall value. Portability varies greatly between types of systems. SMES units, battery storage systems and flywheel ESSs are all now offered commercially as pre-packed, turnkey systems that fit into trailer containers with all of their monitors, controls, and power conversion equipment for easy transportation and installation. For large systems requiring significant energy content, however, portable systems may not be feasible, as the size of the storage media often becomes impractical or uneconomical for transport.

Number and distribution of duty cycle requirements as measured by number of cycles over a specific time period and the way that the cycles occur (at regular intervals, in clusters at intervals, randomly): The type and frequency of duty cycles affects the service life of storage devices. Cycling requirements influence the size and change-out interval for both the storage media and peripheral components. The nature of the duty cycle profile, distribution, and frequency also affect the efficiency of all storage systems. While frequent cycling increases the efficiency of some storage media, it decreases efficiency of others. Frequent cycling also introduces transient effects and associated system inefficiencies that can increase cycle life cost, and can also increase the necessary size of the storage or power electronics, which will increase the cost of the system.

Table 4-3. Summary of Significant Applications Requirements

Application	Power (MW)	Storage (min)	AC Voltage (kVac)	Floor Space (importance)	Portability (importance)	Number/ Distribution of Duty Cycles	Special Demands of the Operating Environment
Rapid reserve	10^1–10^2	10^1–10^2	10^1–10^2	Medium	Low	10^1/year, random, discharge only	Unremarkable
Area control and frequency responsive reserve*	10^1–10^2	Charge – discharge cycles of <10^1	10^1–10^2	Low	Low	Random, continuous charge/ discharge cycles clustered in 2-hour blocks daily	Unremarkable
Commodity storage	10^0–10^2	10^2 – 10^3	10^1–10^3	Medium	Negligible	10^2/year, regular, periodic, weekday block discharge, increased use in shoulder months	Harmonics are more important than in other generation applications
Transmission system stability	10^1–10^2 (MVA)	10^{-3} – 10^{-1}	10^1–10^3	Medium	Low	10^2/year, random, charge and discharge cycles	Unremarkable
Transmission voltage regulation	10^0 – 10^1 (MVAR)	10^1 – 10^2	10^1–10^2	Medium	High	10^2/year, random charge and discharge cycles more likely on weekdays, seasonal by region – at least 6-7 months	Safety concerns are important
Transmission facility deferral	10^{-1} – 10^0	10^2	10^1–10^2	High	High	10^2/year, most likely during weekday peaks, charge and discharge	Safety concerns are important
Distribution facility deferral	10^{-1} – 10^0	10^2	10^0–10^1	High	High	10^2/year, most likely during weekday peaks, charge and discharge	Safety concerns are important
Customer energy management	10^{-2} – 10^1 (MVA)	10^1 – 10^2	10^{-1}–10^1	High	Varies	10^2 to $10^{2/}$year, regular periods	Safety concerns are important
Renewable energy management	10^{-2} – 10^2 (MVA)	10^{-3} – 10^3	TBD	High	High	10^2 to $10^{3/}$year, regular periods, discharge only, unpredictable source	Hostile environments including extreme heat and cold, particulates and corrosive atmospheres
Power quality and reliability	10^{-2} – 10^1 (MVARS)	10^{-3} – 10^0	10^{-1}–10^1	High	Varies	10^2 to 10^2/year, irregular periods, charge and discharge	Safety` concerns are important

*NERC Policy 10, Draft 3 provides details of changes that are under way for Frequency Responsive Reserve. The document is available at http:/ www.nerc.com/~oc/standards/

Table 4-4. Capability of Technologies to Serve Electric Power Applications

Applications	Electrochemical Batteries							Electromechanical Flywheels		Electrical Devices	
	Flooded-Pb/acid	**VRLA**	**Na/S**	**NiMH**	**Li**	**V**	**Zn/Br**	**Steel Rotor**	**Composite Rotor**	**SMES**	**Ultracapacitor**
Rapid Reserve	D	D	P	P	P	P	P				
Area/Frequency Regulation	D	D	P	P	P	P			L	L	
Commodity Storage	D	L	P	P	P	P	P				
Transmission System Stability	D	D	P	P	P	P	P			P	
Transmission Voltage Regulation	D	D	P	P	P	P	P			P	
Transmission Facility Deferral	D	L	P	P	P	P	P			P	
Distribution Facility Deferral	D	L	P	P	P	P	P		P	P	
Customer Energy Management	D	D	P	P	P				P		P
Renewable Energy Management	D	D			P	P	P				P
Power Quality & Reliability	D	D	P	P	P	P	P	D	L	D	P

D – definite capability, L – likely capability, P- possible capability with some charge-control issues. Lithium/polymer is in development and has rudimentary integration (telecommunications only). String limits and PCS integration remain to be established. Participants also agreed that ranking all applications as primary or secondary is important, and that developing groups of primary/secondary combinations is also important.

Value of Storage for Restructured Utility Industry

The electric utility industry in the U.S. is being restructured and is evolving from a regulated monopoly to a partially competitive, partially regulated group of electricity providers. The public's expectation of plentiful, high-quality, and low-cost electricity for all consumers has not changed, and if anything, will grow in the coming years. Generation, transmission, distribution, and use of electricity will be performed in a great variety of new and evolving ways through the implementation of creative regulatory frameworks, financial instruments, and technologies. One technology that could have tremendous impact is energy storage. A study initiated last year by Distributed Utility Associates (DUA) described several scenarios likely for the utility industry in the future.

Status

DUA completed the study, and the final report was received in June 1999. The study describes a series of scenarios in a deregulated utility industry and it discusses the possible benefits from storage in each case.

This report outlines a wide range of innovative ways in which storage could be advantageously used in all aspects of the electric supply system of the future, including customer-sited storage. It discusses ways to expand the envelope of possible storage applications and suggests creative uses for storage. It also presents many possibilities for communicating the value and flexibility of storage.

The report begins with a summary of the assumptions made for the study. These assumptions include continuing state-by-state restructuring with federal restructuring directives lagging behind the states. Generation will be a competitive industry, but T&D will be regulated using performance-based rate-making techniques. While overall electricity rates are assumed to decrease, inequities will exist from state to state and between different classes of customers. Technologies for storing energy will continue to improve, but no dramatic breakthroughs will occur.

A series of scenarios that consider the use of storage in the restructured industry were developed as follows:

1. Core (business as usual with steady evolution)
2. Very inexpensive and efficient storage
3. Environmental emergency
4. Fluctuating electricity price
5. Demanding customer
6. Storage packaging breakthrough
7. Gas and electric industry convergence
8. Energy security
9. Extreme deregulation and competition

The following themes were determined from an assessment of the scenarios.

1. Storage is more likely to be installed at customer sites than coupled to central power plants.

2. An increased interest in environmental issues would accelerate storage technology market entry in many ways; the expanded use of storage is completely consistent with cleaner energy systems.

3. Packaging, ease of use, low initial cost, and high reliability (rather than efficiency and energy density) are the key technology factors in several major market opportunities.

4. Regulatory structures that allow more freedom to solve problems with innovative approaches would be more likely to lead to increased uses of storage.

The implications of each of these themes to electricity providers as well as storage system suppliers and research organizations were also considered.

The final report on the DUA study will be published in FY2000.

Utility Operating Cost Analysis

This task was initiated during FY94 through the placement of a contract with UMR to use EPRI's DYNASTORE computer program to perform calculations of utility operating costs with and without BESS. Operating cost savings are one important component of the battery system cost/benefit picture, along with the system capital cost and other projected utility benefits. In this initial study,* UMR calculated generating costs

* *Assessment of Costs and Benefits of Battery Energy Storage for Electric Utility Applications*, Document AL-9306, revised March 6, 1995, prepared by Dr. Max D. Anderson and John T. Alt.

for a medium-sized utility system (Utility B) that was not interconnected with other utilities. The results of this work showed that significant production cost savings could be obtained by using a battery system for SR.

In FY95, a new contract was placed with UMR for a follow-on study to perform a similar operating cost analysis for a grid-connected utility system.[**] KCPL, which was selected as the subject for this new study, is a typical Midwestern electric utility with many interconnections and a mix of generating plants. As with the previous study, the approach was to run a unit commitment program on energy storage units along with generating units and calculate operating costs with and without energy storage, so that savings could be quantified. This study was completed at the end of the third quarter of FY96, and the greatest production cost savings were projected for frequency regulation applications in this case.

A reanalysis of data from the grid-connected utility system study began in FY97 in order to take into account factors not addressed in the first study, such as battery O&M costs, and to clarify the reasons for certain trends observed in the previous results. UMR studied the impact of fixed and variable BESS O&M costs and found it to be minimal on operating cost savings. A Monte Carlo analysis was used to investigate forced outages. While the Monte Carlo results are viewed as being the most realistic, the differences compared to a deterministic method that does not simulate forced outages were again small in most cases. A final report comparing the results for the island and grid-connected utility cases was submitted during FY98.[***]

Another task that began in FY98 was an investigation of ways to include renewable energy generators in DYNASTORE. Representing the renewable generation as an hourly power purchase transaction proved to be a viable method for including renewables in the DYNASTORE calculations. UMR presented preliminary findings from this task at the end of the fourth quarter of FY98.

Work in this area continued under a new contract placed with UMR during the second quarter of FY99. A major part of this study added the capability to include wind-powered generators in DYNASTORE calculations. The effect of renewable generation on operating costs was also investigated for the KCPL system.

Status

The method used to represent a renewable energy generator in DYNASTORE and assumptions made regarding the generation profile for a 200-MW PV source were discussed in the ESS Annual Report for FY98. Initial DYNASTORE calculations of operating cost savings were carried out with both a BESS and the renewable energy PV source on the KCPL system. This was done for the BESS applications of spinning reserve (SR) only, load leveling (LL) only, and load leveling with spinning reserve (LL + SR) for the years of 1995, 1996, and 1997. Several different BESS powers (40, 100, 200, and 300 MW) and energies (1-hr, 4-hr, and 8-hr duration) were included. These results were compared to earlier DYNASTORE calculations of operating cost savings due only to the BESS (no renewable energy source on the system). The ranges of savings for these two cases are shown in Table 4-5. The differences between the two sets of numbers show the operating cost savings afforded by the PV generator alone. In most cases, the savings resulting from PV alone are greater than the savings resulting from the BESS alone.

Table 4-5. Operating Cost Savings Range ($K/yr) Estimates for KCPL (DYNASTORE Simulation Method: Monte Carlo, 12 Iterations)

Application	BESS Plus Renewable Energy Source	BESS Only
Spinning reserve only	7900 – 11,900	900 – 4800
Load leveling only	6300 – 9000	200 – 4000
Load leveling with spinning reserve	7500 – 13,000	700 – 7600

Savings in Operating Costs Due to Battery Energy Storage System with and without Renewable Sources

To determine savings in operating costs from the BESS in the presence of renewables, the savings afforded by the renewables must be subtracted from the total savings calculated. The resulting savings are then due solely to the BESS. This subtraction was done for a PV source of 200 MW, for all of the BESS applications, SR only, LL only, and LL + SR, for the years 1995 through 1997. The results were presented in Figures 4-1 through 4-9 for the ESS first quarter report in

[**] *A Study to Quantify the Benefits of Adding Storage to a Utility System*, Document AO-4841, revised June 28, 1996, prepared by Dr. Max D. Anderson and Xiangling Gao.

[***] *Electric Utility Savings from BESS Applications*, Document AU-7834, revised August 31, 1998, prepared by Dr. Max D. Anderson and John D. Stickley.

FY99. The BESS application of frequency regulation has also been considered, and is discussed later in this section.

A comparison of these results is as follows:

Spinning reserve (SR) only–savings resulting from BESS are generally higher with 200 MW of PV operating.

Load leveling (LL) only–savings are generally lower because PV is used to shave peaks. Consequently, the BESS is used less.

LL + SR–savings are generally nearly the same because the savings are greater for SR only and less for LL only.

Frequency regulation–PV will increase the need for frequency regulation; hence, BES should be more valuable for this application. With DYNASTORE, the savings afforded by frequency regulation can be evaluated, but the need for frequency regulation cannot. Because PV is dependent upon day/night, cloud cover, and other meteorological conditions, it cannot be considered a reliable energy source for frequency regulation (nor for SR), even though it may be available to pick up the frequency regulation requirement at certain times, thus providing some savings. This lack of PV availability will actually increase the need for frequency regulation, making BESS more valuable (and also more valuable for SR).

DYNASTORE calculates savings in frequency regulation mode by calculating generating unit operating costs for generating units on and off of regulation. The two cost numbers are subtracted to obtain the savings. Using this approach, the benefits of PV would be subtracted out, affording no savings. Other approaches for calculating savings for frequency regulation need to be investigated.

The calculated results enable the following conclusions:

1. Renewable sources (PV in this case) actually feed into the load, causing the BESS to be used less for the LL application. The hourly PV generation profile has a shape similar to the hourly load profile, except that the load profile may lag the PV generation profile by two or more hours. Hence, the PV generation will aid in serving part of the peak load.

2. When renewable generation sources are in use by the system, a smaller-size BESS may be adequate in some cases. The calculations show a smaller increase in savings with larger BESS size for the LL only application if the PV source is present.

3. Use of PV increases the need for frequency regulation as well as SR. This is due to the periods that PV may be unavailable or have reduced power output because of day/night times, cloud cover, or other meteorological variables.

In the second quarter, a new contract was placed with UMR to continue modeling electric utility cost savings afforded by BES with renewable energy sources. A major part of this study is to develop the capability to include wind power generators in DYNASTORE.

Wind speed data used in this project were obtained from the Solar and Meteorological Surface Observational Network (SAMSON). The data set is available from the National Oceanographic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC). The set is divided geographically into regions: Eastern, Central, and Western United States. It contains hourly solar radiation data along with selected meteorological elements for the period 1961–1990. It encompasses 237 stations in the United States, plus stations in Guam and Puerto Rico. The data set includes both observational and modeled data. The hourly solar elements are extraterrestrial horizontal and extraterrestrial direct normal radiation, and global, diffuse, and direct normal radiation. Certain meteorological elements are also recorded. These are total and opaque sky cover, temperature and dew point, relative humidity, pressure, wind direction (true north) and speed, visibility, ceiling height, present weather, precipitable water, aerosol optical depth, snow depth, days since last snowfall, and hourly precipitation. The data were originally developed by a joint effort between NCDC and the National Renewable Energy Laboratory (NREL).

The wind energy resource atlas of the United States shows the areas that are potentially suitable for wind energy applications are dispersed throughout much of the United States Estimates of the wind resource in this atlas are expressed in wind power classes ranging from Class 1 to Class 7, with each class representing a range of mean wind power density or equivalent mean speed at specified heights above the ground. Areas designated Class 4 or greater are suitable with advanced wind turbine technology under development today. Power Class 3 areas may be suitable for future generation technology (year 2000 and beyond). Class 2 areas are marginal and Class 1 areas unsuitable for wind energy development. The South Central region, consisting of Arkansas, Kansas, Louisiana, Missouri, Oklahoma, and Texas, has Class 3 or higher annual average wind power. A map of the of annual average wind power, along with wind power classifications, is presented in Figure 4-1. The average wind power in Missouri is shown in Figure 4-2.

During the third quarter, a model for estimating the electrical power available from wind in the KCPL area was constructed. The three steps involved in calculating the power from the wind are shown below.

1. Calculate wind speeds for 12 typical weeks from the 30 years of data available from the NCDC.

2. Translate wind speeds from recorder height to turbine hub height.

3. Calculate electrical power from wind speed at hub height.

Step 1: *Evaluation of wind speed for 12 typical weeks from 30-year data.* Hourly wind speeds are available for 30 years from 1961 through 1990. The following procedure was used to get data from 12 typical weeks, one week for each month of the year. Considering one month at a time, average wind speeds were found for each hour of each day of the month. In this way, 30 months of data (the same month each year for 30 years) is replaced by a single month with average hourly wind speeds. Then, by similar averaging, a typical week is found for the month. This is repeated for all the months. At the end of this procedure, we have 12 typical weeks of hourly wind speed data, one for each month of the year. Figure 4-3 shows the average wind speeds at ground level for a representative day in January. It should be noted that Figure 4-3 is not intended to represent actual wind speeds in any given day because it is derived from averaging. These average values are useful for predicting mean power levels generated by the wind turbines, but in the final analysis, the variation about the mean must also be included. This will be done in follow-on work.

Step 2: *Calculation of wind speeds at hub height.* The wind speed is measured at the height of the anemometer – typically ground level. Because the wind turbine blades will be at a different height from the anemometer height, the recorded wind speeds must be translated to the hub height before power can be calculated. Zond Energy Systems, Inc., is one of a handful of wind turbine manufacturers in the United States that produces large turbines. Their 750-kW Z-50 turbine, which has been successfully used in the United States and abroad, was used for wind power calculations. According to machine specifications, the hub height is 65 m and the blade diameter is 50 m, yielding a total swept area of 1963 m^2. The wind speed at a 65-m hub height can be calculated using the one-seventh power law. The power law (Equation 1) states that the wind speed at a height of z2 will be

$$u(z2) = \left(\frac{z2}{z1}\right)^{\alpha} * u(z1)\,, \qquad (1)$$

where:

z1 = the height at which wind speed was measured
z2 = the height at which wind speed is to be calculated
u(z1) = wind speed at height z1
u(z2) = wind speed at height z2

In Equation 2, typical values of constants a and b were used to calculate α

$$\alpha = a - b * \log(u(z1)), \qquad (2)$$

Typical values of 0.11 and 0.061 in the daytime and 0.38 and 0.209 at night. For the months of March through September daytime is 6 a.m. to 8 p.m., and for the remaining months daytime is 7 a.m. to 5 p.m. The wind speed measurement height is 10 m. Wind speeds at the hub height were calculated for the 12 typical weeks.

Step 3: *Calculation of wind power.* Based on the above wind speeds, wind power was calculated using the formula given by Equation 3. Using this equation, wind-generated powers are calculated for all 12 typical weeks that were required by the DYNASTORE program. Figure 4-4 shows the average power generated by the Zond Z-50 WTG for a representative day in January.

$$P = 0.5\rho\, A\, C_p\, V^3 N_g N_b \qquad (3)$$

where:

P = power in watts,
ρ = air density (about 1.225 Kg/m^3 at sea level; this value is taken even though Kansas City is 315 m above sea level)
A = rotor swept area = 1963 m^2 from specifications
C_p = coefficient of performance = 0.35
V = wind speed in m/sec
N_g = generator efficiency = 0.8
N_b = gearbox/bearings efficiency = 0.9

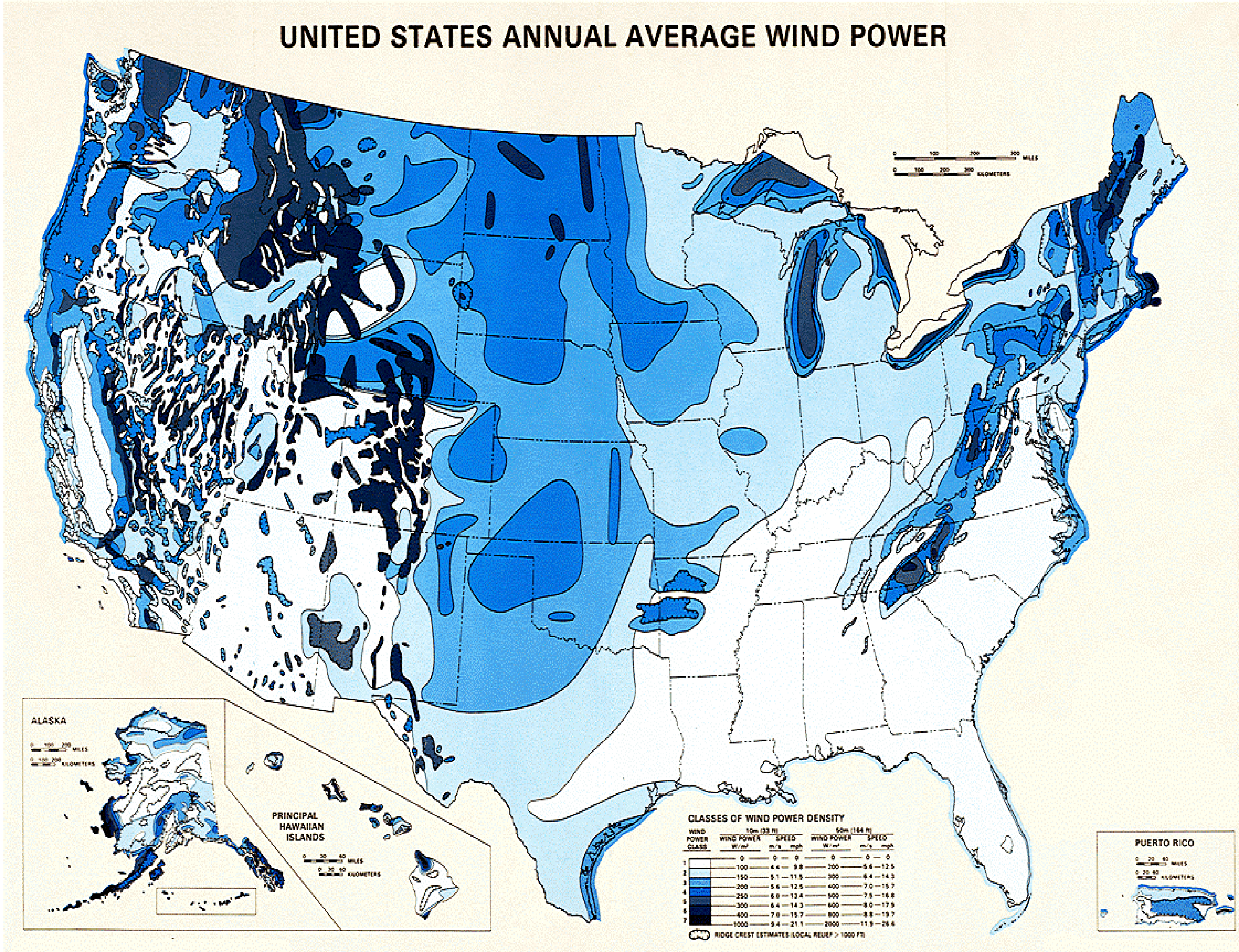


Figure 4-1. A Map of Annual Average Wind Power, along with Wind Power Classifications.

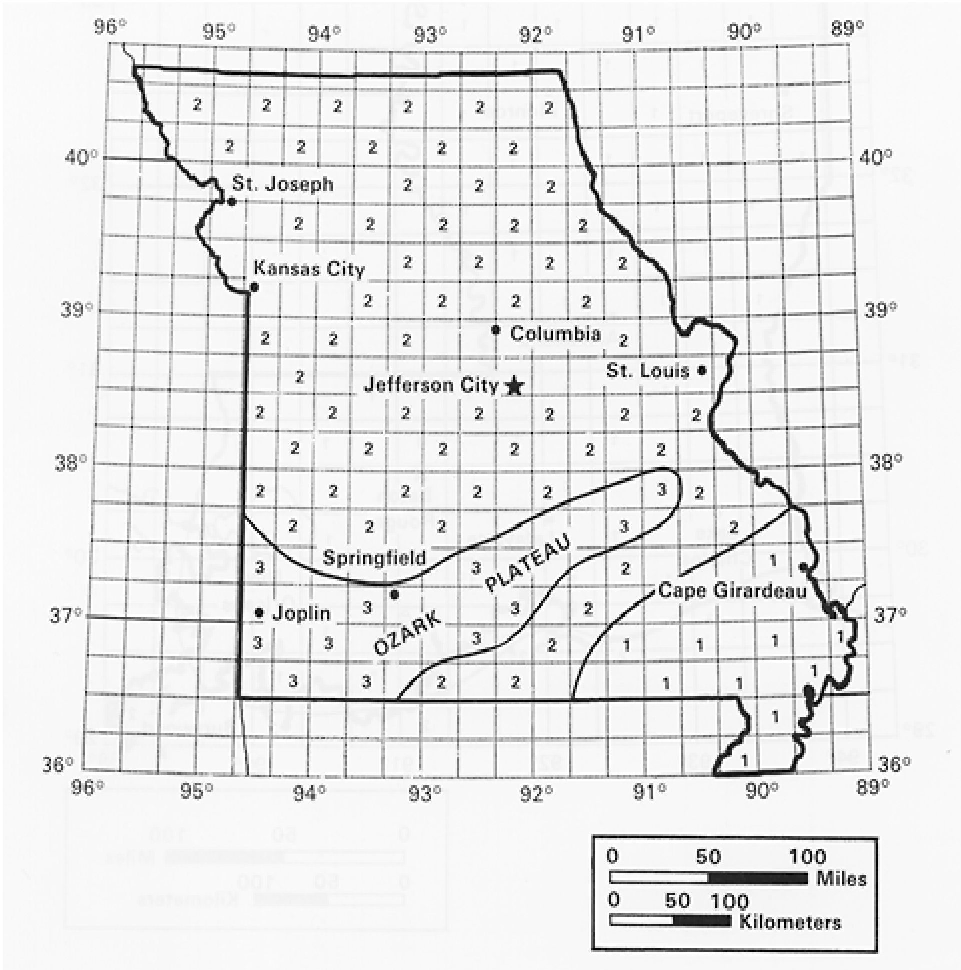


Figure 4-2. Average Annual Wind Power in Missouri.

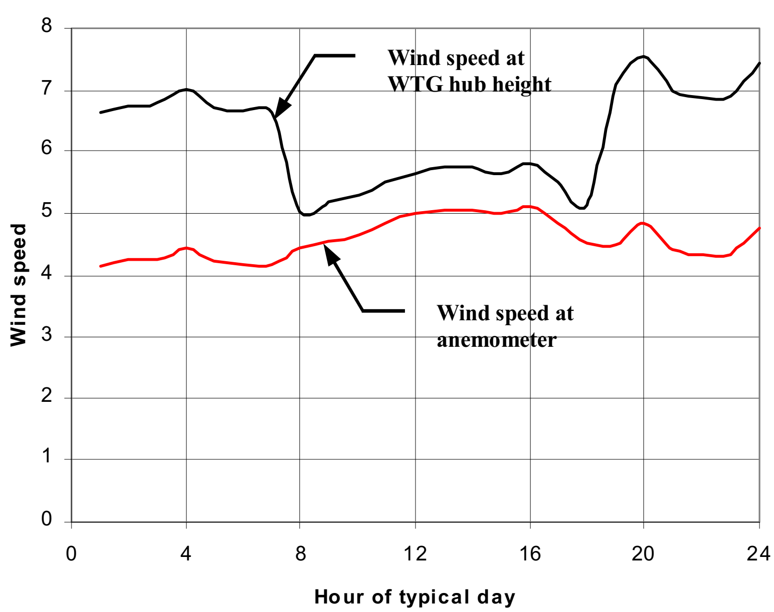


Figure 4-3. Average Wind Speeds at Anemometer and Hub Height for a Representative Day in January.

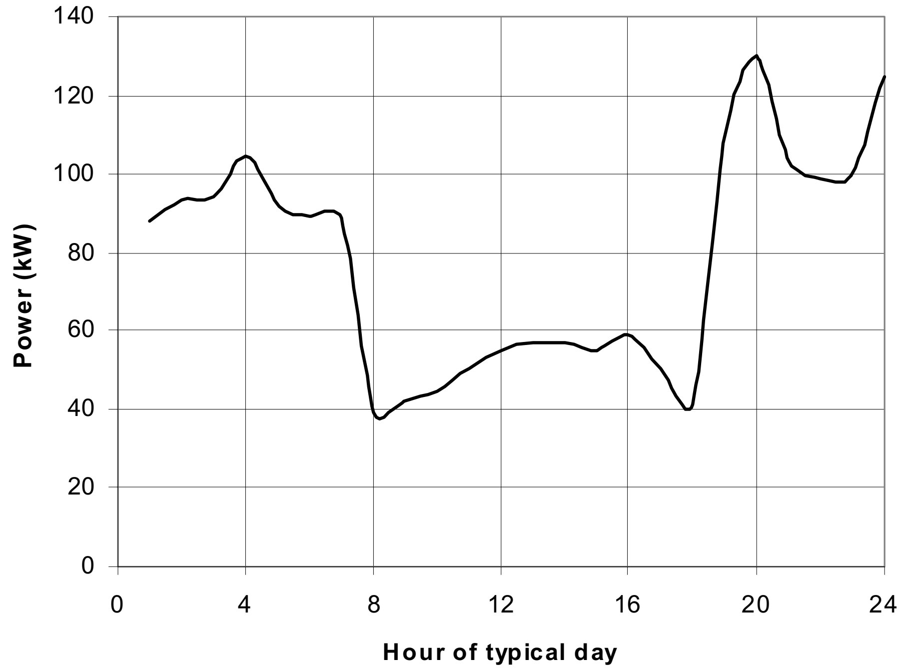


Figure 4-4. Average Power Generated by the Z-50 Wind Turbine Generator (WTG) on a Representative Day in January. Averaging Method Was Used.

The above calculations enabled production of input data for the DYNASTORE program. With these data in hand, UMR completed DYNASTORE calculations. In order to make realistic calculations of the operating cost data with wind power included in the generation mix, UMR assumed a 400-MW capacity from the wind farm. This is expected to result in 200 MW of actual wind power some of the time, which should be comparable with the PV generation. In the PV case, a peak generation capacity of 200 MW was used. The DYNASTORE runs were being made for the BESS cases of 40-, 100-, 200-, 300-MW capacity and 1-, 4-, and 8-hr duration. The modes of BESS operation were SR only, LL only (PS), and LL + SR. The years for the study were 1995, 1996, and 1997. This is the same format used in previous studies, which will enable comparisons to be made to previous results. Savings in operating costs for each BESS application for each year are shown in Figures 4-5 through 4-13. A complete listing of the results is given in Appendix B.

The results to this point have shown savings in operating costs when energy storage is present on a utility system. The estimated values vary by factors of two to three, depending on the particular application for the energy storage and the utility configuration with regard to interconnections. Some typical values are shown in Table 4-6 for a grid-connected electric utility. SR is generally the application showing the most savings due to BESS, while PS/LL shows the least savings.

Table 4-6. Operating Cost Savings Range ($K/yr) Estimates for KCPL (DYNASTORE Simulation Method: Monte Carlo, 12 Iterations)

Application	BESS Plus 400-MW Wind Power Source	BESS Only
Spinning reserve only	23,400 – 30,300	900 – 4700
Load leveling only	21,800 – 26,000	200 – 4000
Load leveling with spinning reserve	23,000 – 31,000	700 – 7600

Analysis of the situation with renewables is complicated and is still not complete, but an indication is emerging that the operating cost benefits of storage in this case may be much larger than previously estimated. The reason for this is that renewable energy sources are not continuously available (e.g., PV at night) and therefore cannot be allocated to certain applications, such as SR, that require 100% availability. However, the use of energy storage will broaden the range of applications to which renewables can be applied by providing the capability to ride through periods of low renewable generator output. Therefore, the storage not only directly

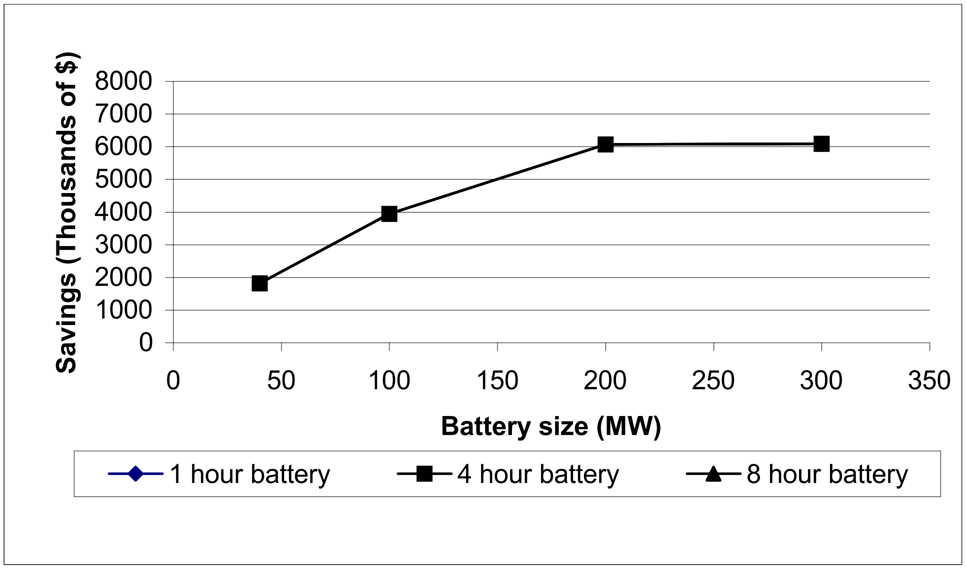


Figure 4-5. **Operating Cost Savings with a BESS Used for Spinning Reserve Only by KCPL (1995) after Subtraction of the Savings Afforded by a 200-MW Wind Generator (Simulation Method: Monte Carlo, 12 Iterations).**

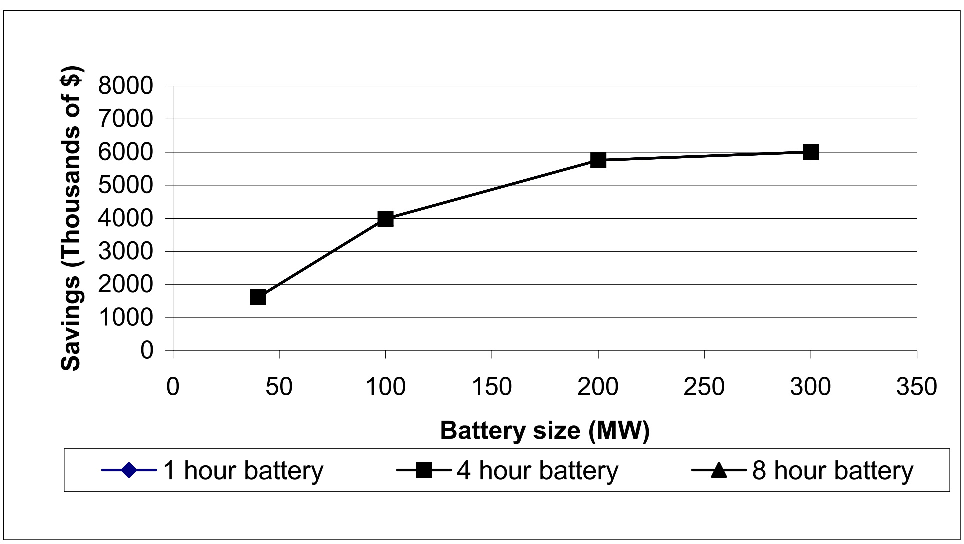


Figure 4-6. **Operating Cost Savings with a BESS Used for Spinning Reserve Only by KCPL (1996) after Subtraction of the Savings Afforded by a 200-MW Wind Generator (Simulation Method: Monte Carlo, 12 Iterations).**

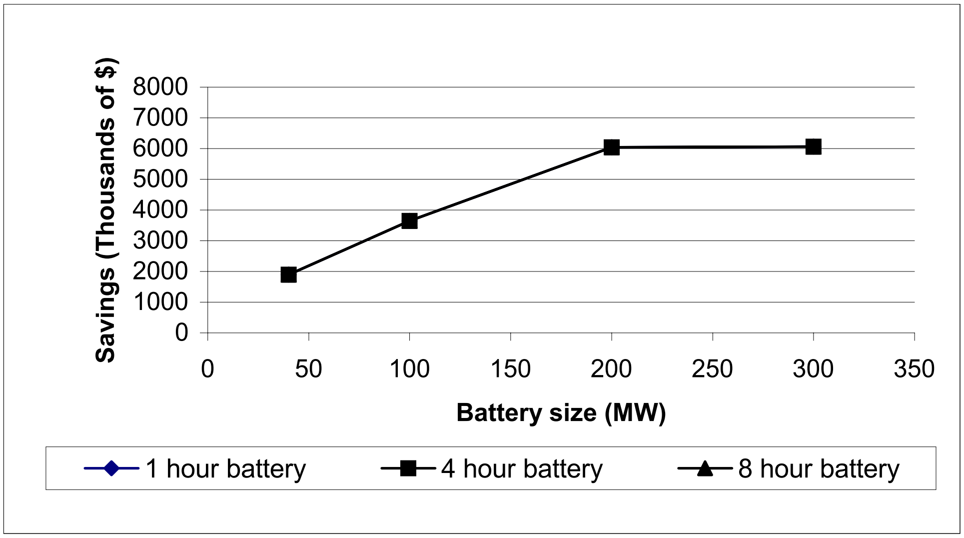


Figure 4-7. **Operating Cost Savings with a BESS Used for Spinning Reserve Only by KCPL (1997) after Subtraction of the Savings Afforded by a 200-MW Wind Generator (Simulation Method: Monte Carlo, 12 Iterations).**

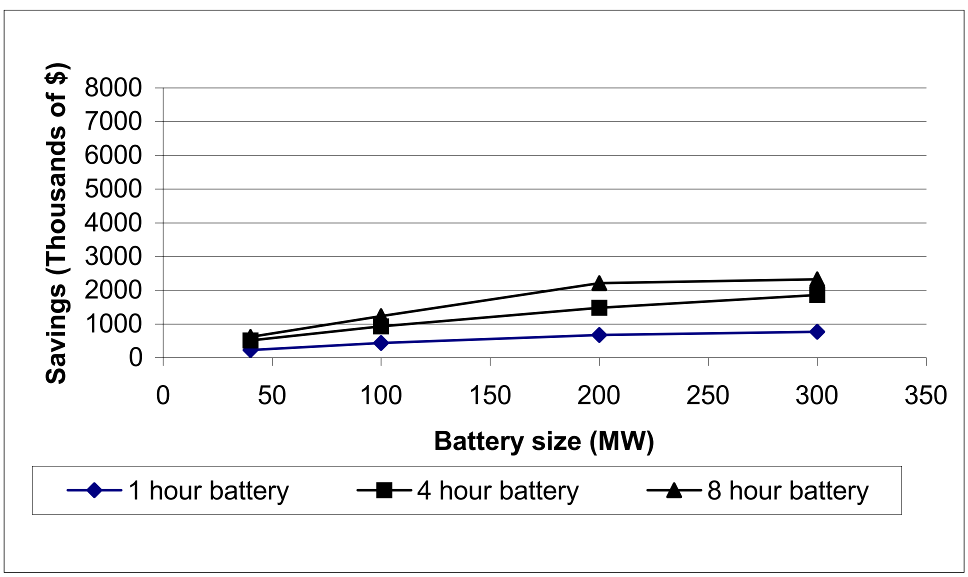


Figure 4-8. **Operating Cost Savings with a BESS Used for Load Leveling Only by KCPL (1995) after Subtraction of the Savings Afforded by a 200-MW Wind Generator (Simulation Method: Monte Carlo, 12 Iterations).**

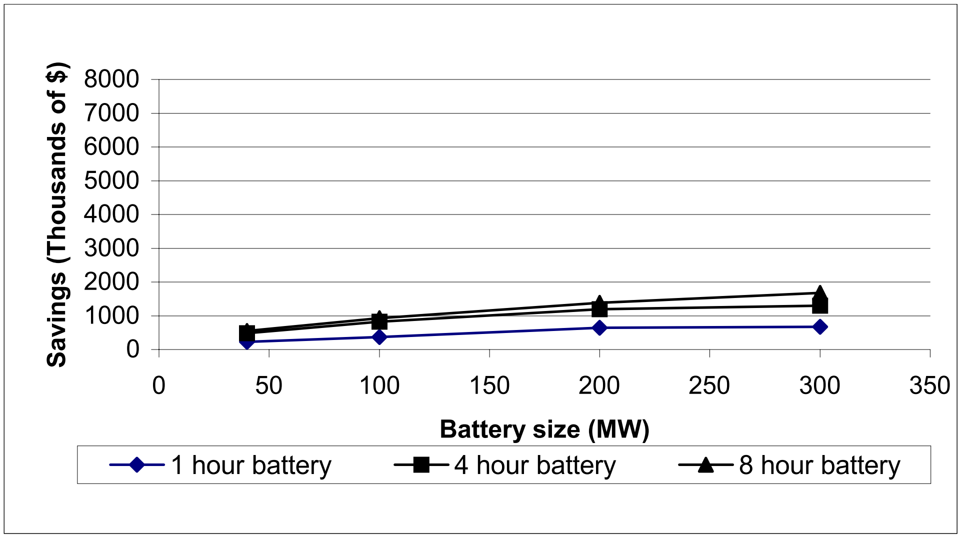


Figure 4-9. Operating Cost Savings with a BESS Used for Load Leveling Only by KCPL (1996) after Subtraction of the Savings Afforded by a 200-MW Wind Generator (Simulation Method: Monte Carlo, 12 Iterations).

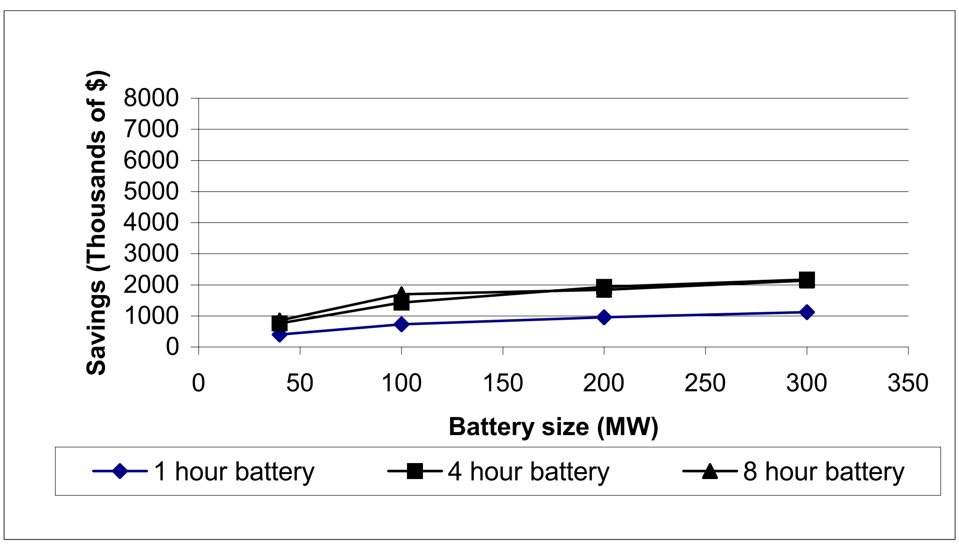


Figure 4-10. Operating Cost Savings with a BESS Used for Load Leveling Only by KCPL (1997) after Subtraction of the Savings Afforded by a 200-MW Wind Generator (Simulation Method: Monte Carlo, 12 Iterations).

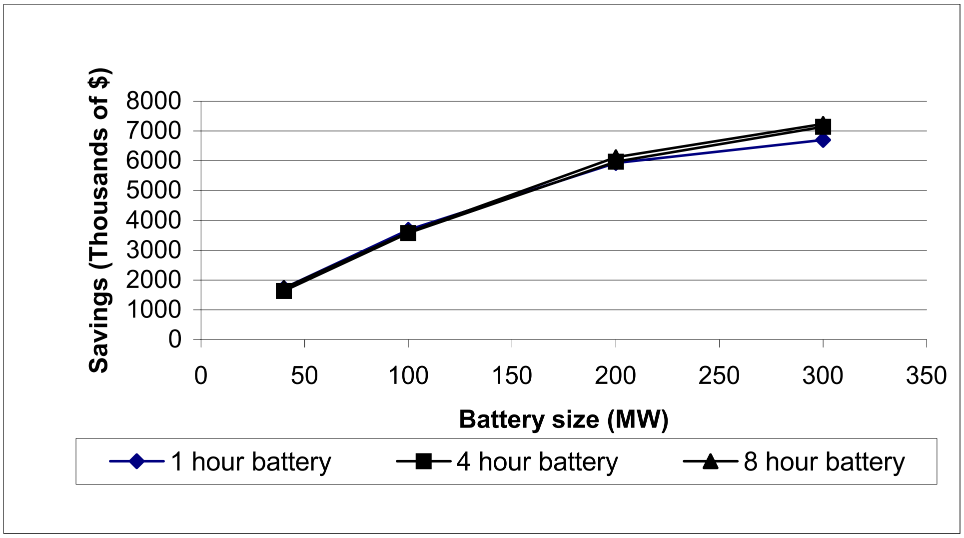


Figure 4-11. Operating Cost Savings with a BESS Used for Load Leveling with Spinning Reserve by KCPL (1995) after Subtraction of the Savings Afforded by a 200-MW Wind Generator (Simulation Method: Monte Carlo, 12 Iterations).

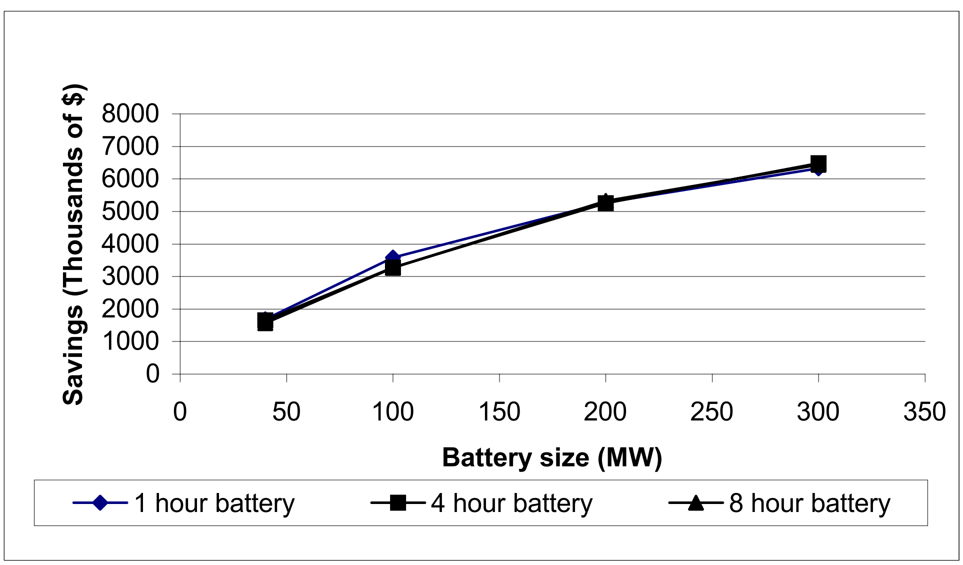


Figure 4-12. Operating Cost Savings with a BESS Used for Load Leveling with Spinning Reserve by KCPL (1996) after Subtraction of the Savings Afforded by a 200-MW Wind Generator (Simulation Method: Monte Carlo, 12 Iterations).

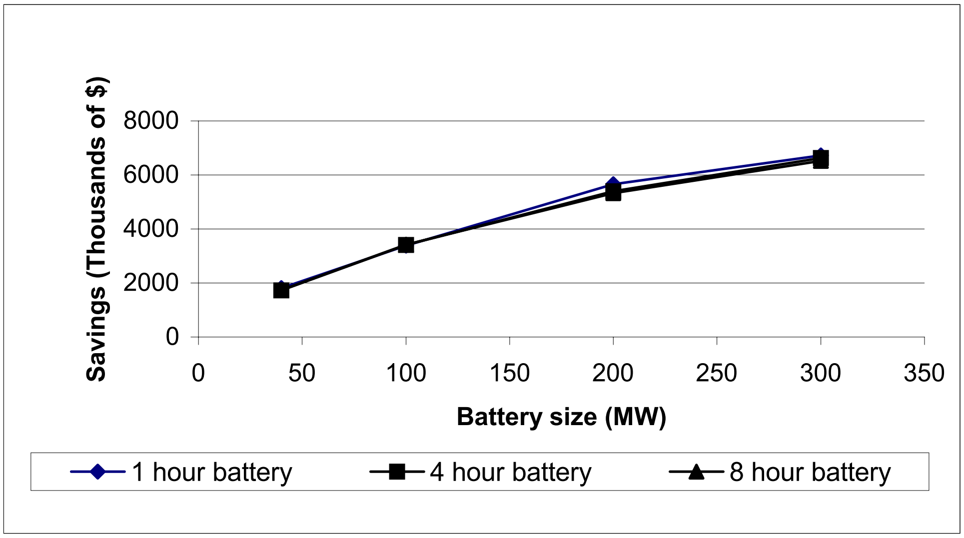


Figure 4-13. Operating Cost Savings with a BESS Used for Load Leveling with Spinning Reserve by KCPL (1997) after Subtraction of the Savings Afforded by a 200-MW Wind Generator (Simulation Method: Monte Carlo, 12 Iterations).

replaces more expensive sources of generation, such as combustion turbines, it also enables renewable generation to serve many of these applications. Since renewables generally have very low operating costs, this significantly increases operating cost savings. As shown in Table 4-6, these savings can be quite large, four to six times greater than those from adding BES alone to a utility system.

The low end of the savings ranges shown in Table 4-6 reflects a BES power of 40 MW and a 1-hr duration while the high end corresponds to 300 MW of BES power with an 8-hr duration. For reference, this utility has a summer peak load of about 3,000 MW and the total generating capacity is around 5,000 MW. Annual operating costs were estimated by DYNASTORE to be \$115M per year without any wind generation or BES; therefore, a savings of \$30M per year represents a 25% reduction in operating cost. Although the calculation of cost/benefit ratios is not the focus of this study, it is worth pointing out that the cost of 40 MW of 1-hr BES could be recovered within roughly two years at this savings rate.

The savings figures shown assume that energy storage allows the renewable wind generation to be fully allocated to the indicated applications, and that the wind generation is always "on" for an amount calculated by statistical averaging. However, we know that the output of wind and solar energy generators can vary considerably over a period of time. It is intuitive that a BESS is necessary to "take up the slack" in power for any wind or solar facility in order to make it a suitable energy source for certain applications. In fact, the variable nature of the renewable generator output is expected to make energy storage even more valuable when this type of generation is present. However, the extent of use of BESS and the savings in the case of variable renewable generator output have not yet been quantified. Including the full effect of variability in renewable generator output will be a major focus of the next phases of this study. The strategy for use and level of acceptance of renewable generation sources by system operators is also unclear due to the relatively low penetration of renewables in the utility market.

International Energy Agency Annex IX

The DOE Office of Power Technologies is the United States participant for the International Energy Agency (IEA) Implementing Agreement for Research and Development on Energy Conservation through Energy Storage. In June 1996, the OPT made a commitment to participate in the recently created electrical Energy Storage Annex IX by pledging funding in support of its activities. The primary benefits of United States participation are increased awareness of analytical and technical developments in storage in the international arena, identification of projects of mutual interest, and the ability to assess the competitive position and market opportunities for energy storage systems in the overseas markets. ILZRO is also interested in these objectives and has contributed funding for participation by the United States in Annex IX.

OPT and ILZRO designated the ESS Program at SNL to be the USA Participating Agent in the activities of Annex IX. This responsibility requires attending executive committee and experts meetings in the United States and abroad, coordinating United States representation by experts for the various storage technologies, and identifying projects of common interest to the participants and supporting the implementation of the projects.

Status

Phase 2 of Annex IX *Electrical Energy Storage Technologies for Utility Network Optimization* work was concluded at the end of FY99. A final report, which was an overview of this work, was submitted in November 1999. Topical reports on Subtasks 1, 2, and 3 were submitted in the third and fourth quarters of FY99.

- Subtask 1: Applications Case Studies
- Subtask 2: Project Definitions
- Subtask 3: Applications Modeling

A summary of these reports follows:

Subtask 1: Applications Case Studies—The Case Studies report was received in the third quarter of FY99 and represents the final output of Subtask 1.

The report focuses on storage systems as solutions for specific problems. It is aimed at users who may be relatively unfamiliar with storage. Preexisting electrical energy storage installations are described from the perspective of the end user as distinct from the particular storage technology employed.

Four different broad application categories are considered.

- Power quality/quality of supply,
- Distribution capacity deferrals/peak shaving/ demand-side management (DSM),
- Integration of renewables, and
- Frequency regulation/spinning reserve/stability

Where possible, attention is drawn to factors deemed important in project management of the installations, with a view toward learning lessons for future storage installations. The decision-making processes for a potential user of electricity storage are discussed under the following headings:

- System cost,
- System benefits,
- System performance, and
- Time scales of installation and of expected system lifetime.

Power Quality/Quality of Supply

The following is a background and performance summary of two of the systems reviewed as part of the case studies addressing the power quality application.

In 1996, Oglethorpe Power Corporation installed a 1-MW, 10-second battery storage system at a lithography plant in Homerville, Georgia. The system was designed to remedy voltage sags and short power outages with a 4-ms response time. The system uses flooded lead-acid batteries and features a transportable container (4.5 m long × 2.3 m wide × 3.7 m high; weight = 18.1 tons).

The initial cost of this system was $1.06M, and it has an estimated discounted life cycle cost over 20 years of $1.65M. Costs of similar systems are said to have diminished since this installation.

Construction began in May 1996, the containerized equipment arrived in July 1996, and operation began in December 1996. From December to July 1996 more than 50 supply disturbances were successfully dealt with.

The South African National Electricity Company Eskom installed a 2.4-MJ low-temperature SMES system at a paper mill in Stranger, South Africa. The objective was to remedy voltage dips due to flashovers induced by lightning, sea mists, and fires. Steady voltage is essential for accurate motor speed control in paper mills.

The South African installation is a relatively small "micro-SMES PQ-VR" model. High-temperature superconducting connectors are used in the newest installations to minimize losses in the resistive parts of the system.

The Stranger paper mill installation was commissioned in April 1997. The system had achieved 100% reliability up to February 1998, even through 68 voltage dips, about half of which would have been serious enough to stop production at the mill, were it not for the storage system.

Distribution Capacity Deferrals/Peak Shaving/ Demand-Side Management

The following is a summary of one of the systems reviewed as part of the case studies addressing distribution capacity deferrals, peak shaving and DSM.

GNB Technologies is a major U.S. battery manufacturer and operates a lead smelting and recycling center in Vernon, California. Large electric fans are crucial to the plant's environmental protection measures, and are vulnerable to power failures. The company has a strong commercial interest in the development of battery storage systems and therefore installed a system to demonstrate the viability of the technology.

The plant's maximum load is 5 MVA, critical load 2.1 MVA, and typical load 3.5 MVA. The BESS peak rating is 5 MW/5 MWh and runs the whole plant for 10 seconds during non-critical load shedding and then the critical load for up to two hours.

In the event of long power outages, an orderly shutdown is possible, with the critical loads continuing to be supplied by the battery. As well as its principal backup function, the BESS has been used for peak shaving to generate electricity purchase savings.

Costs of the BESS were considered against a continuously operating motor-generator flywheel system, coupled with a diesel engine. The former provides only limited time of operation, but has low parasitic costs, compared with the 200 kVA, \$0.1M per year of the motor generator. Overall the discounted life cycle costs were deemed similar, but these estimates depend upon battery life. The BESS cost \$4.2M, against \$4.5M for the alternative.

The system is not considered cost-effective solely on the basis of peak shaving and demand reduction; the overriding rationale is maintenance of environmental safety through power outages.

The project was announced in November 1994, construction began in January 1995, and was completed in August 1995. The plant was fully commissioned in January 1996.

Startup of the BESS takes less than one second. The system performs routine automatic peak lopping at a preset power demand. Fifty percent capacity is retained for emergency backup.

Overall benefits include:

- Environmental safety assurance
- Savings in peak demand charges for utility
- Peak tariff unit charges avoided

Integration of Renewables

The following is a background and performance summary of two systems reviewed as part of the case studies addressing the integration of renewables application.

A lead-acid battery storage system consisting of three modules totaling 1.2 MW and 1.2 MWh for peak shaving and power quality improvement, was installed at Herne-Sodingen, Germany, for the local utility Stadtweke-Herne AG. The storage system at Herne operates in parallel to a PV plant, which became operational in the summer of 1999. The battery itself has operated in a peak-load shaving mode since December 1997.

It was deemed more cost effective to install the storage system than to build utility network extensions. The principal applications envisioned for the scheme were integration of the renewable generation resource, load leveling, and power quality improvements, as well as the deferral of new capacity. Also, it was intended to assist in the development of process automation for storage systems.

Planning, preparation for construction, and construction took two, eight, and eleven months respectively. Construction ran from January to November 1997. The battery has operated in peak shaving mode since December 1997, and was deemed fully commissioned in February 1998. A PV plant was operational and integrated in the summer of 1999. The customer paid about half the cost, with government and international agency grants covering the rest. The storage medium accounted for 40% of the capital costs, and the interface plus the power conversion system for 20%.

Frequency Regulation & Spinning Reserve

The following is a background and performance summary of a system reviewed as part of the case studies addressing frequency regulation, spinning reserve, and stability applications:

Dinorwig is a pumped hydro facility on the edge of the Snowdonia National Park in North Wales and is the largest storage facility in Europe, constructed as a major national investment when UK generating capacity and the national grid were under monolithic state control.

The system has ratings of:

- 1800 MW max (6 × 300 MW motor/generator)
- 1380 MW × 5h = 6900 MWh

Eighty percent full generating power can be achieved in 10 seconds if the generators are kept spinning in air in synchronization with the grid, taking 5 MW per machine. Electrical storage turnaround efficiency is about 67%.

It is used principally for frequency control and emergency backup for major plant failures on the UK National Grid. There are smaller 360-MW pumped storage schemes nearby at Ffestiniog, and another in Scotland at Cruachan.

Costing $425M in 1975, construction of the system was the largest civil engineering contract to date in the UK. Construction began in 1974 and took 10 years to complete.

This project now seems out of scale with the diversity of the privatized UK electricity supply industry, and has to compete with many suppliers. This illustrates the potential investment pitfalls when a long-term view is taken in modern energy markets.

It is unlikely that the planning of such a project in the future could overcome the environmental objections.

Case Studies Conclusions

The major conclusions from the case studies work are as follows:

- Planning takes a long time (often years), but to avoid pitfalls, careful consideration is worthwhile.
- A "turnkey" approach is always desired by the end user, but a constructive partnership is essential among planners, suppliers, consulting engineers, and end users.
- Construction often takes approximately a year, except in the case of trailer-mounted turnkey installations.
- Careful monitoring and documentation of initial testing, subsequent performance, and problems are highly desirable because of the immaturity of the technology.
- Modularity and standardization of system assemblies will reduce costs, improve reliability, and diminish the demands on the system designers and engineers.
- It will often be difficult to make a sound cost-benefit case relative to fossil-fuelled generation options; the storage field is still in an exploratory phase and will mature in the future.

Subtask 2: Project Definitions—The report was completed in the third quarter of FY99 and represents the final output of Subtask 2. The Project Definition Report focuses on two energy storage applications: power quality (Table 4-7) and primary substation applications (Table 4-8). The report presents a cost breakdown for the various electrical energy storage system solutions currently available. Generic information is provided without focusing on any single suppliers' solution or any particular site.

Table 4-7. Power Quality Installation Application

Power rating	2 MVA, 2 seconds (typical)
Energy storage capacity	1 to 2 kWh or 3 to 6 MJ (typical)
Storage technology	Batteries (including lead-acid and advanced battery technologies)
	SMES
	Flywheels
	Capacitors
	Supercapacitors
	Hybrid (i.e., combination of above)

Table 4-8. Utility Substation Application Specifications

Power rating	2 to 4 MVA, 15 mins to 2 hours (typical)
Energy storage capacity	1 to 4 MWH (typical)
Storage technology	Batteries (including lead-acid and advanced battery technologies)
	Hybrid system (i.e., incorporating a flywheel, SMES, capacitors, super-capacitors, etc.)

Key system features include:

- Modularity of system configuration,
- Transportability (i.e., ease of relocation),
- Re-configurable functionality, and
- Remote on-line monitoring.

Power Quality Project Definitions

Reasons for the choice of the power quality application follow:

Power quality and quality of supply are of growing importance as electronic devices form an increasingly large proportion of overall electrical load. Electronic motor drives are becoming widespread in manufacturing industry. They, and other power electronic devices and computer-related equipment can both be susceptible to and themselves cause electricity supply disturbance. The full range of practical electrical energy storage systems can be applied to many power quality applications, so this application provides an interesting project definition, with much scope for innovative development and demonstration.

Based on work carried out in Phase 1 of Annex IX and subsequently, it was judged that an appropriate installation for the costing study would be sized at:

- 2-MW rating for a duration of up to 2 seconds of continuous supply, i.e., 1 to 2 kWh or 3 to 6 MJ.

A "quality of supply" application would ideally have a ride-through of the 10 seconds needed for electromechanical protection systems such as auto-reclosers to operate after fault clearance, when possible. However, shorter durations are common in current storage installations, on grounds of storage cost, but clearly offer a lesser degree of protection. It was decided to cost a "power quality" application rather than one on "quality of supply" as defined above. The latter application would always have to have storage capacity and switchgear capable of supporting the whole load, whereas a power quality application would generally need to support only a part of the total load.

This application is highly relevant for network operators, as it impinges upon another topic of increasing importance, i.e., asset management. In increasingly competitive and liberalized modern energy markets, effective use of assets is clearly of enormous economic significance.

Substation Project Definition

Storage can play a role in avoidance of network reinforcement, alongside alternatives such as localized generation. Unlike the latter, however, storage systems can perform a secondary power quality function within the same installation. Local embedded generation is, in many cases, more likely to create rather to than solve short-term power quality problems.

It was judged that a suitable project of this kind would be a primary substation application with a ration of:

- 2 to 4 MW for a time of up to 30 minutes of continuous supply, i.e., 500 to 2000 kWh or 1800 to 7200 MJ.

Cost Estimates

The estimated costs for a power quality application, as defined previously, are shown in Table 4-9. The cost of supercapacitors is not included, as no cost information is available, but the technology is included in the study because of its excellent future potential.

A breakdown of the initial costs involved with the purchase, installation, and commissioning of energy storage devices for a substation application are shown for the four storage technologies in Table 4-10.

As with the power quality application, the equipment to load interface cost will vary depending upon the rating of the storage device. The type of storage medium used will not normally affect the cost of the connection and is therefore valid for most applications. The connection of any electrical equipment to a network must obviously meet strict safety requirements that will make certain fixed costs unavoidable irrespective of capacity. The expected cost for such an application with a 2-MW rating is in the range $40K to $60K. This cost may diminish in the future to the same degree as the power quality application, due to modularization. These figures are estimates derived from total project costs from the literature and known costs for the appropriate elements of similar applications.

In the case of the advanced and conventional battery storage systems, a solid state switch is fitted to the network interface to allow the rapid isolation of the storage system in the event of a network fault. The purpose of the switch is to avoid the storage system "feeding back" into the faulted network. The slow reaction time of the compressed air energy storage system is such that a conventional mechanical isolation switch can be used.

Table 4-9. Initial Cost Breakdown for a 2-MW, 2-sec Power Quality Application

	Battery (BESS) ($K)	Flywheel (FES) ($K)	Superconducting Magnet (SMES) ($K)	Supercapacitor (S-CS) ($K)
Storage medium				
High	100	600	800	
Low	80	400	600	
Interface				
High	60	60	60	60
Low	40	40	40	40
PCS				
High	825	825	1000	825
Low	360	360	800	360
Other				
High	1000	1200	1800	1000
Low	500	700	1000	500
Total				
High	1985	2685	3660	
Low	980	1500	2440	

Table 4-10. Initial Cost Breakdown for a 2-MW, 2-MWh Substation Application

	Battery (BESS) ($1K)	Advanced Battery, e.g., Redox Flow Cells ($1K)	Compressed Air (CAES) ($1K)
Storage medium			
High	600	4065	700
Low	400	1100	500
Interface			
High	160	160	60*
Low	140	140	40*
PCS			
High	825	825	825
Low	360	360	360
Other			
High	1500	1500	1500
Low	1000	1000	1000
Total			
High	3085	6550	3085
Low	1900	2600	1900

* No fast-acting switch for protection required because of reduced system reaction time.

The PCS is typically 15 to 20% of the overall cost of a substation application. Cost will be in the range \$360K to \$825K for a typical system. Again, these estimates are derived from literature values for total and partial costs for similar installations.

Future cost reductions are likely as power electronic systems advance. However, the scope for standardization will be less for this application than for the power quality case, since there are likely to be fewer and more varied substation installations.

The cost of the energy storage medium for this application often represents the largest single element in the total cost breakdown, at around 20 to 30% for battery installations.

There are some cost categories that do not fall into the initial cost categories listed above. These costs consist of taxes incurred, site considerations, transportation, financing, and other services that add significantly to the initial costs of each project.

As in the power quality application, the choice of technology for this substation application is best viewed in terms of cost versus tangible benefits. The battery energy storage solution has all the advantages and disadvantages as pointed out above for the power quality application, but with an even greater need for a rigid and stable base with the increased battery capacity required for this application. The increased maintenance and battery replacement needed for a larger scale system might also make a battery solution less attractive in the long term.

Advanced battery technologies at this stage entail some technical risk. These systems offer enhanced storage densities and therefore smaller footprint than the better established lead-acid technology. In most other respects they are generally equivalent. A key difference is that redox flow type batteries have an added feature of being able to decouple their power and energy rating, since the parameters are determined by different elements within the battery system. Thus, the power rating is determined by the cell stack design, while the energy storage rating is determined by the volume of electrolyte stored in separate tanks. Redox flow cells represent a promising development in the field of advanced battery research.

Each of the candidate advanced battery systems has its own potential environmental difficulties (as have conventional, established battery systems). The particular chemical used will have a strong bearing on the cost of necessary safety precautions, and these have not been explored fully for many of the emergent technologies.

Compressed air energy storage (CAES) systems use proven industrial technologies. The low cost per kilowatt claimed by one developer in their prequalification document indicated this may be a relatively cheap storage method.

Development of flywheel technology has been focused on smaller capacity devices, e.g., 5 kW/5 kWh. Larger capacity devices are under development, e.g., 100 kW/5 kWh, making them unlikely contenders for this application in the short term. One flywheel company launched their “new pirouette” flywheel in May 1999, which will be rated at 100 kW/3.2 kWh and will be capable of being cascaded to more useable levels of storage.

Each of the storage technologies has an associated risk; for example, the potential for lead-acid battery problems resides primarily in acid spillage, and secondarily in lead release in the event of fire. These risks are in addition to the risk of sudden release of the stored energy, common to all storage systems. Storage of very large volumes of either toxic or relatively innocuous chemicals for a redox flow system would be subject to environmental and safety regulation.

The project definitions work provides indicative costings for two applications of electrical energy storage. The intention is that these be used to generate proposals for future demonstration installations, incorporating innovations and advances in the technology.

Subtask 3: Applications Modeling—Work on this subtask was nearing completion in the fourth quarter of FY99. A final report was received in October 1999 and represents the final output of Subtask 3.

The purpose of the power quality application model is to help the user to design an energy storage system to meet the needs and requirements placed on it. The model uses a benefit/cost calculation to give the optimum system scaling for a given set of parameters. The model consists of a stand-alone executable written in Borland Delphi (32 bit) for use with MS Windows 95/NT/98 or above.

It is intended that the model be used by system designers to help make the decision whether energy storage is viable, which storage technology is best suited, and to define the optimal system scaling in terms of power and energy requirements for a particular scenario.

The user must input the voltage level (and number of phases) and peak load current for the application(s) to be "protected." The user must input approximate figures for the cost of each of the levels and duration of voltage dip; this is possibly the most difficult and least accurate approximation.

However, this thought process is part of the most basic economic analysis of the energy storage system application. The user should consider the following cost categories when attempting to quantify the cost of each voltage dip:

- Cost of lost production
- Cleanup cost
- Equipment damage
- Cost of waste/scrapped materials
- Reduced equipment life span (years)
- Reduced product quality

The model uses the above information to calculate the benefit matrix. Figure 4-14 shows the modeled benefit of mitigation at different voltage magnitudes and durations. The user then inputs cost information for an energy storage system in terms of $/kW and $/kWh. The voltage connection level and rms current are used to calculate the power and energy requirements over a range of dip durations. From this information, a cost matrix is calculated. The user can employ a variety of system costs for comparison using different storage media, and in this way cost comparisons of different storage technologies can be made. Figure 4-15 shows a three-dimensional plot of the modeled cost of a typical energy storage system. It is clear that the cost rises rapidly with both increasing dip duration and reducing voltage magnitude.

Dividing the benefit matrix by the cost of the matrix gives the benefit/cost matrix. The optimal benefit over cost ratio will be seen as the maximum value in this matrix and will identify the best system scaling for the user's specification.

Figure 4-16 shows a three-dimensional plot of a cumulative benefit/cost. The peak value, at 75 to 80% retained voltage magnitude and a duration between 10 and 20 mains cycles, indicates that this is the most economic range of events for which to design a system.

From the optimized dip duration, shown in Figure 4-16, the voltage level and the peak current, the required power and energy levels for the system can now be calculated.

Network Simulation Integrated Model—As there are a variety of software packages available to the network designer to simulate network performance, each with its own merits, a specification for this model has been produced that can be applied to any of the major packages that are commercially available. The specification was written in accordance with the guidelines laid down by the IEEE Standard 830-1993–IEEE Recommended Practice for Software Requirements Specifications.

The scope of the specification for the network applications modeling of energy storage systems is clearly defined as covering the following areas:

- A model definition suitable for use with any of the commonly used network simulation packages.

- The model will cover the applications of distribution capacity deferrals, peak shaving, frequency regulation, spinning reserve, and stability.

In carrying out this work a number of software manufacturers were contacted and questioned about the possibilities of integrating energy storage system components into their packages. The overall response from these companies was that when they experience a significant demand, they would then act to integrate storage into their packages.

In addition to the above requirements for modeling/load flow analysis, this integrated energy storage model must incorporate economic factors and be able to simulate the interaction of the storage device with the network over a time frame long enough to realize the benefits the system was designed to fulfill.

Transmission Power Quality Study

The Transmission Power Quality (TPQ) study will monitor and define power quality levels of the electric transmission system for a defined 13 state region in the Southeastern United States. A previous study conducted by the Electric Power Research Institute (EPRI) characterized power quality levels of the distribution system. However, very little data now exist for customers of a transmission network. Many large industrial facilities get their power directly by the transmission network without a distribution system. Data captured from this study will assist the ESS Program in the design and scope of the Substation Power Quality project, which is intended to mitigate power quality disturbances from the transmission system. This project will provide utilities with baseline data for system performance, and experience in a large-scale

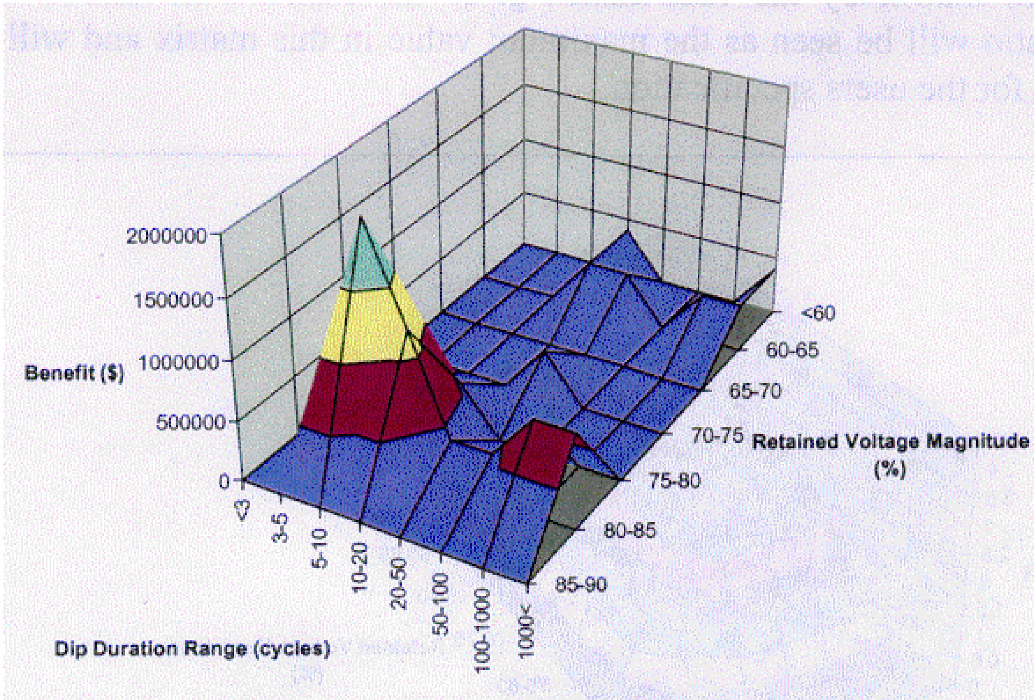


Figure 4-14. Plot Showing the Modeled Benefit of Mitigation at Different Levels.

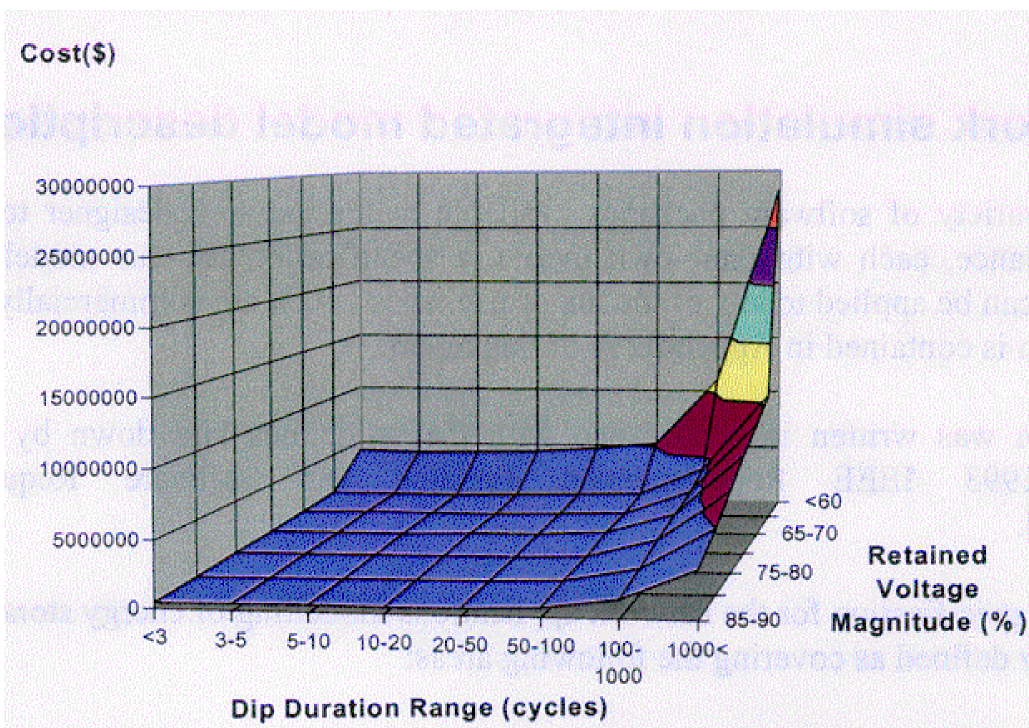


Figure 4-15. The Modeled Cost of an Energy Storage System.

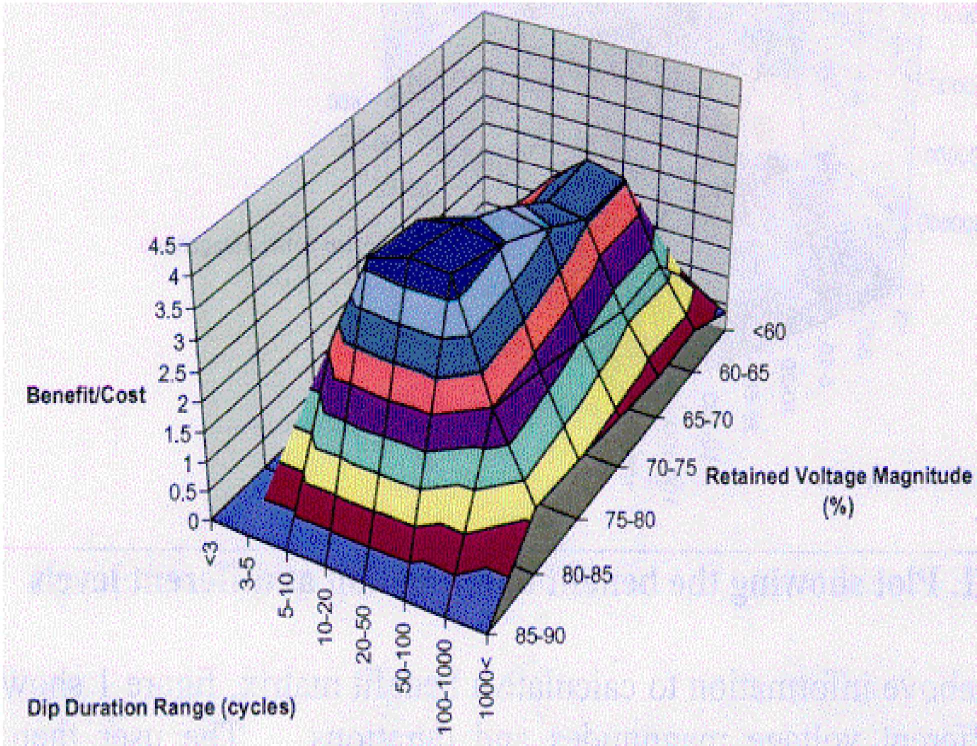


Figure 4-16. Cumulative Benefit/Cost.

monitoring project. Also, the resulting data may be used to validate system models for studies on the behavior of the transmission system. This study will also provide valuable data for the DOE's Electric Reliability Initiative.

Status

A study team composed of representatives from utilities, SNL, EPRI, and the Southeastern Electric Exchange (SEE) conducted a scoping study that outlined the project justification, methodology, cost information, and schedule. Monitoring sites will be chosen throughout the Southeast to provide a statistically valid sample of the transmission system. Criteria for choosing sites are voltage class and lightning stroke density. Participating utilities will procure, install, download, and maintain appropriate monitoring equipment. Data from the participating utilities will be transferred to EPRI, which will serve as a central collection point. EPRI will compile the transferred data into a composite database, removing all utility-specific information. The database will be transferred to SNL for further analysis and characterization. SEE will serve as a facilitator for the project, recruiting participants and hosting project review meetings and workshops. The DOE will provide funding for the project, in conjunction with cost-sharing from industry. DOE will also coordinate the ESS program with other SNL programs that may benefit from this study.

The Southeastern United States was chosen for the monitoring region for TPQ. Thirteen states have been identified, as shown in Figure 4-17, based on geographic interpretations of a "Southeastern" boundary, and the location of participating utilities in the SEE. This organization is comprised of member utilities in the Southeastern U.S. for the purposes of sharing information on operational practices such as safety and benefits all members. The SEE also serves as an excellent central point for disseminating information to prospective participating utilities.

Statistical analysis concludes that a minimum of 300 sites must be selected to provide a statistically valid sample. The duration of the monitoring period will be a minimum of 24 months. A minimum of 11 utilities will be required to participate, with five specific utilities identified as necessary participants based on the number of potential monitoring sites and size of the service territory. Total project cost is estimated at $7.3M over the four-year life of the project. Cost-sharing opportunities exist with industry participants, including the use of existing monitoring equipment and installations, utility and SEE labor, and development of data analysis and management software.

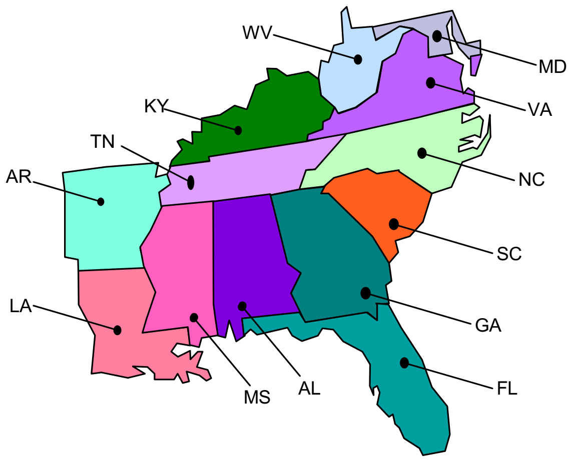


Figure 4-17. The 13-State Region Under Study Defined as the Southeastern U.S.

Table 4-11 lists the utilities in these 13 states that own transmission assets. Most of these utilities are SEE members; however non-SEE members will be invited to participate in the study. Likewise, EPRI membership (or lack thereof) has no bearing on whether or not a particular utility may participate in the study.

Table 4-11. Potential Participating Utilities

Utility	States Covered
American Electric Power (AEP) (*Only southern operating region considered for study*)	VA, WV, KY
Allegheny Power	WV, VA, MD
Baltimore Gas & Electric (BG&E)	MD
Cleco Corporation	LA
Carolina Power & Light (CP&L)	NC, SC
Duke Power	NC, SC
Entergy	LA, MS, AK
Florida Power & Light (FP&L)	FL
Florida Power Corporation (FPC)	FL
Jacksonville Electric Authority	FL
Kentucky Utilities	KY
Louisville Gas & Electric (LG&E)	KY
Georgia Transmission Corp	GA
Potomac Electric Power (PEPCO)	MD, VA, DC
South Carolina Electric & Gas (SCE&G)	SC
Southern Company*	GA, AL, FL, MS
Tampa Electric Company (TECO)	FL
Tennessee Valley Authority (TVA)	TN
Utilicorp	WV
Virginia Power	VA, NC

* Southern Company comprised of member companies: Georgia Power, Mississippi Power, Alabama Power, Savannah Electric, and Gulf Power

Technology Assessments

Performance and Economic Analysis of Superconducting Magnetic Energy Storage, Flywheels, and Compressed Air Energy Storage Systems Project

The scope of the ESS Program includes a portfolio of energy storage technologies for electric utility applications. The program approach has been to apply expertise gained from work with BES to the development of storage media, PCSs, peripheral devices, and advanced storage systems that depend on similar components. The ESS Program initiated this analysis project with Energetics, Inc., in FY97 to identify the areas in which program expertise directly applies to this expanded range of technologies and where such program expertise must be developed.

Status

The final report, *A Summary of the State of the Art of Superconducting Magnetic Energy Storage Systems, Flywheel Energy Storage Systems and Compressed Air Energy Storage Systems*, was published in July 1999, and can be referenced in SNL's Technical Library using the following number SAND99-1854.

Long- Versus Short-Term Storage Study

A study to characterize the stationary applications and technologies of short- and long-term energy storage was completed by the ESS Program. Applications of energy storage have a wide range of performance requirements. One important requirement is storage time or discharge duration. In this study, applications and technologies have been evaluated to determine how storage time requirements match technology characteristics. Comparisons have also been made on the basis of capital cost for various ESSs operating over a range of discharge times, categorized as short term (< 2 hr) and long term (2 to 8 hr). Special categories of very short term (< 1 min) and very long term (a day to weeks) were also considered. The technologies evaluated included batteries (lead-acid and advanced), flywheels (low and high speed), supercapacitors, SMES, compressed air energy storage (CAES), pumped hydro, and hydrogen.

Status

A draft copy of the report has been received and is under review. The following is a brief summary of the draft report:

The areas that have long been the focus of the ESS Program's R&D of energy storage for the utility sector are reliability, expanded use of renewables, and enhanced utility/industry productivity. Energy storage can address and benefit these areas in a variety of ways. Applications in these areas can be more specifically categorized by the functions that are recognized by utilities and their customers. These applications include:

Load management—Load management includes the traditional load-leveling application of energy storage, in which energy is stored during off-peak hours (typically at night) and then discharged during peak hours. This not only saves money on the basis of the difference between peak and off-peak rates, but also provides a more uniform load factor for the generation, transmission, and distribution systems. Other types of load management are ramping and load-following.

Remote power—In some remote locations it is not practical to bring power to a site from an established utility grid. Power may be generated from diesel or gas generators, fuel cells or renewable sources. For local load management, it may be useful to include energy storage to minimize the generation capacity.

Spinning reserve—Most electric utilities operate with a requirement for SR. This generation is ready, or in "hot standby," should an electric generating unit somewhere on the system fail. The available reserve power is determined by the configuration and mix of unit capacities on the system. Typically, the reserve power must equal the power output of the largest generating unit in operation.

Renewables matching—Renewable energy sources, such as wind and solar, are desirable because they are non-polluting and in plentiful supply. By their very nature, however, they are intermittent; often the profile of energy generation does not coincide with the demand cycle. Energy storage can be used to match the output of renewable sources with any load profile.

Transmission enhancement—Energy storage can improve transmission capacity by providing line stability, voltage regulation, frequency regulation, and volt amp reactive (VAR) or phase angle control. Specialized power electronic equipment must be located in suitable locations along transmission lines. The amount of energy injected is often small, but at relatively high power.

Distributed resources—Distribution systems in many growing urban and suburban areas are subject to dramatic daytime peaking. It is often more cost-effective to add distributed generation resources in critical locations than to upgrade distribution wires. Energy storage can be ideal for this application because recharging can take place during off-peak periods.

Power quality—Utility power sometimes suffers disturbances such as momentary voltage sags or even outages. These events, along with harmonic distortions and other imperfections, can affect sensitive processing equipment that needs extremely clean power to operate properly. ESSs are being successfully installed to provide reliable, high-quality power to sensitive loads. Sometimes the systems are coupled directly to the critical equipment, and sometimes to the bus feeding a facility or even on a feeder line.

End use—Although the primary end-use application for energy storage is for power quality, there are other customer uses. These include local PS (to avoid time-of-day charges) and process enhancements (e.g., in pulsed power processes, or other specialized industrial applications).

Transit—Many electric transit systems could benefit from energy storage because of the highly variable load they create during braking and start-up. Many types of energy storage can provide regenerative braking, accepting energy from the propulsion system during deceleration and then providing a boost during acceleration.

These applications can also be characterized by their technical requirements, i.e., power level, energy storage capacity, and response time. The energy storage capacity is specifically determined by the time duration delivery or discharge. Applications tend to fall into time categories of very short, short, long, and very long.

Cost Analysis

One major objective of this study was to compare system capital costs for the various technologies in several representative applications. For those systems that consist of the energy storage unit and a single PCS that operates in both the discharge and charging modes, the system cost is the sum of the component costs plus balance of plant (BOP).

The costs and efficiencies used in this study are listed in Table 4-12. Most of these were developed through discussions with vendors while others are found in recent literature. These values represent the latest available data and projections. Table 4-13 indicates the relative maturity of the technologies and certainty in the cost assumptions.

Performance Fit

Technologies can be matched to applications in a variety of ways. Certainly cost can be a deciding factor. But the performance must also meet the application requirements. The most important characteristics are power, stored energy, and response time. If a technology cannot provide all of these characteristics, it is not suited to the application. Figure 4-18 shows numerous ESSs plotted by characteristics of power delivered and energy stored. Overlaid on the chart are lines indicating discharge times of one second, one minute, and one hour. The plot is logarithmic and covers a wide range of time scales. Some general application areas are indicated, for example, power quality, load management, and distributed utility.

After considering the performance fit and capital costs, Table 4-14 is presented to summarize the technologies that best fit the various applications, and their characteristics.

Some general conclusions from Figure 4-18 are:

- Ultracapacitors are best suited for smaller applications, i.e., end use.
- Batteries and SMES cover the broadest range of applications, from less than a MW to thousands of MW.
- For very large power applications, only a few technologies are suitable—CAES system and pumped hydro.

Figure 4-19 indicates typical response times for the various technologies. Those with solid-state power conversion interfaces can often respond at subcycle rates, assuming they are on "standby." Those with mechanical inertia, such as air or water turbines, require longer start-up or response time. Most fuel cell systems also require warm-up or flow time, but recent advances are making quick-response fuel cells available as well.

The various energy storage technologies serve some applications better than others do. Distinctions can be made on the basis of long- or short-term storage (or discharge duration), size (power level), response time, and also on the basis of cost.

Some conclusions from this study include:

- Flywheels are a good match for a range of short-term applications up to a size of several MW.
- Batteries currently have the broadest overall range of applications.
- Fuel cells should be applicable and cost-effective in a very broad range of applications in the future.
- Hydrogen–fueled combustion engines are a currently available technology for short-term applications including distributed utility applications, renewables matching, and SR.
- CAES and pumped hydro are best for load management when geology is available and response time in the order of minutes is acceptable.
- SMES is a niche technology for power quality and especially high-power distribution or transmission networks. Projected costs for bulk storage, however, show it to be expensive.

In this study, only capital costs were considered. It is recommended that operating costs also be considered, because the different technologies have different energy efficiencies, parasitic requirements or losses, operations and maintenance cost; some include fuel costs and different lifetimes or replacement costs.

It is also recommended that fuel storage options for hydrogen systems be considered more broadly. In power quality applications, for example, it is possible to simply deliver hydrogen to the site, rather than use an on-site electrolyzer to produce it. This may be more cost-effective. Finally, a sensitivity analysis to cost assumptions would be valuable.

Table 4-12. Energy Storage Technologies Costs and Efficiencies

	Energy Related Cost ($/kWh)	Power-Related Cost ($/kW)	Balance of Plant ($/kWh)	Electrolyzer ($/kW)	Compressor ($/scfm)	η, Discharge Efficiency
Lead-acid batteries (low)	175	200	50			0.85
(average)	225	250	50			0.85
(high)	250	300	50			0.85
Power quality batteries	100	250	40			.85
Advanced batteries	245	300	40			0.7
Micro-SMES	72,000	300	10,000			0.95
Mid-SMES (HTS projected)	2000	300	1500			0.95
SMES (HTS projected)	500	300	100			0.95
Flywheels (high-speed)	25,000	350	1000			0.93
Flywheels (low-speed)	300	280	80			0.9
Ultracapacitors	82,000	300	10,000			0.95
Compressed air energy storage (CAES)	3	425	50			0.79
Compressed air storage (CAS) in vessels	50	517	50			0.7
Pumped hydro	10	600	2			0.87
Hydrogen fuel cell/ gas storage (low)	15	500	50	300	112.5	0.59
Hydrogen fuel cell/ gas storage (high)	15	1500	50	600	112.5	0.59
Fuel cell/ underground storage	1	500	50	300	112.5	0.59
Hydrogen engine/gas storage	15	350	40	300	112.5	0.44

Table 4-13. Comparison of Commercial Maturity and Cost Certainty for Energy Storage Technologies

Technology	Commercial Maturity	Cost Certainty
Lead-acid batteries	Green	Green
Power quality batteries	Red	Yellow
Advanced batteries	Red	Red
Micro-SMES	Yellow	Yellow
Mid-size SMES	Purple	Purple
Superconducting magnetic energy storage (SMES)	Purple	Purple
Flywheel (high-speed)	Red	Red
Flywheel (low-speed)	Yellow	Green
Ultracapacitor	Red	Red
Compressed air energy storage (CAES)	Yellow	Yellow
Compressed air storage (CAS) in tanks	Purple	Purple
Pumped Hydro	Green	Yellow
Fuel cells (conventional)	Yellow	Yellow
Fuel cells (dynamic response for power quality)	Red	Red
Hydrogen combustion engine	Yellow	Green
Green	Mature products, many sold	Price list available
Yellow	Commercial products, multiple units in the field	Price quotes available
Red	Prototype units in the field	Costs determined each project
Purple	Designs available	Costs estimated

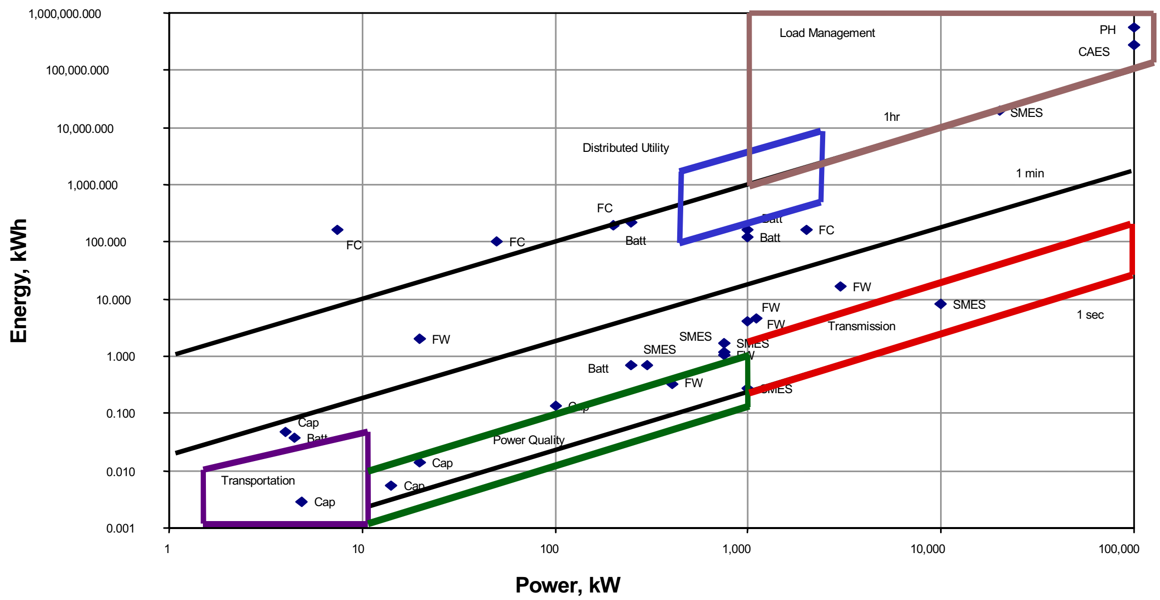


Figure 4-18. Power and Energy Characteristics of Energy Storage Products.

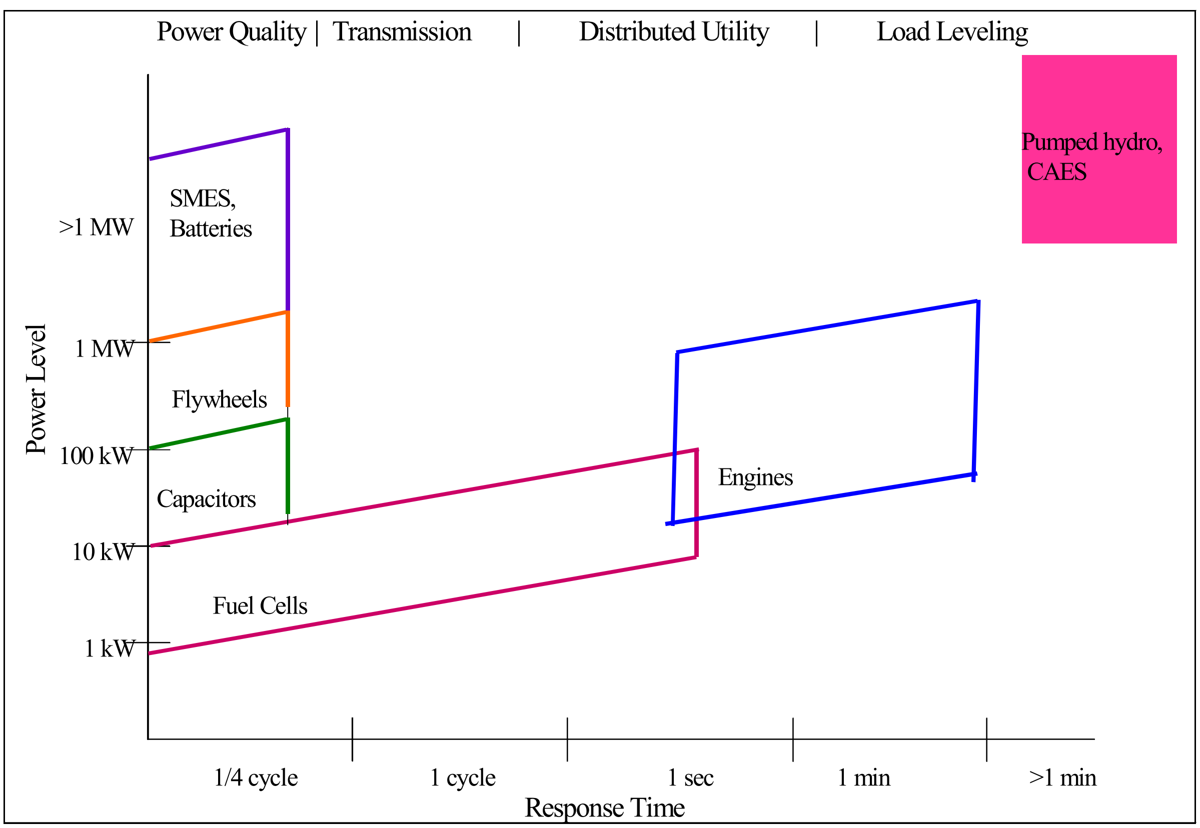


Figure 4-19. Response Characteristics of ESSs.

Table 4-14. Applications, Characteristics, and Appropriate Technology

APPLICATION	Power	Storage Time	Energy	Response Time	Technologies
Very short duration			**kWh**		
End use ride-through, power quality, Motor Starting	1 ≤ MW	secs	~.2	< 1/4 cycle	Flywheel Ultracapacitors Micro-SMES Lead-acid battery H_2 fuel cell
Transit	< 1 MW	secs	~.2	< 1 cycle	Flywheel Ultracapacitors Micro-SMES Lead-acid battery H_2 fuel cell
T&D stabilization	up to 100's MW	secs	20 - 50	< 1/4 cycle	SMES H_2 fuel cell Lead-acid battery
Short duration			**kWh**		
Distributed generation (peaking)	.5 to 5 MW	~1 hr	5000 - 50,000	< 1 min	Flywheel Advanced batteries SMES Lead-acid batteries Fuel cell or engine CAS
End use PS (to avoid demand charges)	< 1 MW	~1 hr	1000	< 1 min	Flywheel Advanced batteries Lead-acid batteries SMES Fuel cell or engine CAS
Spinning Reserve—rapid response within 3 sec to avoid automatic shift	1 - 100 MW	< 30 min	5000 - 500,000	< 3 sec	Flywheel Lead-acid battery Advanced battery SMES Fuel cell or engine CAS
Conventional response within 10 min	″	< 30 min	″	< 10 min	Flywheel Lead-acid battery Advanced battery SMES Fuel cell or engine CAES CAS Pumped hydro
Telecommunications backup	1 - 2 kW	~2 hrs	2 - 4	< 1 cycle	Flywheel Ultracapacitors Lead-acid battery Advanced battery H_2 fuel cell
Renewable matching (intermittent)	up to 10 MW	Min - 1 hr	10 - 10,000	< 1 cycle	Flywheel Lead-acid battery Advanced battery H_2 fuel cell SMES

(continued on next page)

Table 4-14. Applications, Characteristics, and Appropriate Technology (continued)

APPLICATION	Power	Storage Time	Energy	Response Time	Technologies
Uninterruptible Power Supply	up to ~2 MW	~2 hrs	100 - 4000	sec	Flywheel Lead-acid battery Advanced battery SMES CAS H_2 fuel cell H_2 engine
Long duration			**MWh**		
Generation, Load leveling	**100s** MW	6-10 hrs	100 - 1000	min	SMES Lead-acid battery Advanced battery Pumped hydro CAES CAS H_2 fuel cell H_2 engine
Ramping, load following	**100s** MW	several hrs	100 - 1000	< cycle	SMES Lead-acid battery Advanced battery H_2 fuel cell
Very long duration			**MWh**		
Emergency backup	1 MW	24 hrs	24	sec – min	Lead-acid battery H_2 engine H_2 fuel cell CAS Advanced battery
Seasonal storage	50 - 300 MW	weeks	10,000 - 100,000	min	CAES
Renewables backup	100 kW -1 MW	7 days	20 - 200	sec – min	Battery Advanced battery CAES CAS Pumped hydro H_2 fuel cell/underground storage

Power Conversion System Magnetics and Functionality Analysis

A previous study* conducted by the ESS Program focussed on identifying the state of the art in PCS technology and identified several promising research directions whereby cost and footprint reductions could be achieved. Additionally, the study cited several areas that could potentially contribute to cost reduction, but available information did not permit a thorough assessment. The following list contains two promising ideas that could not be adequately evaluated.

1. Simplify PCS specifications by defining the minimum functionality required for a PCS used as part of an ESS.

2. Improve the magnetics used in the PCS.

The purpose of the work being undertaken at this time is to further evaluate the above areas. As such, this report is an extension of and relies heavily on the

* Atcitty, S., S. J. Ranade, and A. Gray-Fenner, *Summary of State-of-the-Art Power Conversion Systems for Energy Storage Application*, SAND98-2019, Sandia National Laboratories, Albuquerque, September 1998.

previous study. The objective of Task 1 is to determine if there is a standardized approach to specifying PCS functionality that can reduce cost in ESSs. The objective of Task 2 is to determine if significant savings can be achieved in cost and footprint for PCS magnetic components.

Status

The PCS is a vital part of all ESSs. It provides the means for transferring power and energy between different energy sources such as AC power systems and generators, DC battery storage systems and DC PV sources. The PCS performs conversion from DC to AC, for example, to supply energy from batteries to a load. One of the ESS Program's goals is directed at improving the power conversion process in terms of reliability and cost.

The study approach consisted of developing an assessment of current designs, identifying benefits through discussion with vendors and through a survey of literature, and developing a cost-savings assessment. Discussions were held with five organizations, two involved in the RGS area, one involved in the UPS area, one expert in motor control design, and a power semiconductor manufacturer.

In order to provide a better focus, the scope of this study was limited to grid-independent RGS systems. An RGS system may consist of photovoltaics as a renewable source, BES, and an engine generator serving a load. Such a system may include several power conversion subsystems, namely, the DC-AC inverter, a DC-DC battery charge/discharge controller, and possibly an array peak-power tracker. These subsystems, along with the controller, may be integrated in a single package as the PCS. This report is concerned with the inverter.

PCSs use inductors and capacitors and, more generally, filters for waveform control and to support basic energy conversion mechanisms. Transformers are often required to interface to the AC load. These components are collectively referred to as magnetics.

In the survey described the earlier study, many vendors indicated that there is significant potential for footprint and cost reduction in the magnetics part of the PCS. Therefore it was considered worthwhile to explore the issue further. The approach, again, primarily involved discussions with vendors.

Some vendors suggested that in conventional PCS, magnetics represent 20 to 30% of the cost and contribute 30 to 50% to footprint and weight. Some RGS vendors prefer to use off-the-shelf magnetics because the low product volume precludes custom design or in-house design and construction. Off-the-shelf or third-party supplied magnetics are often designed using low-frequency design approaches. When used in a PCS, where the current and voltage contain high-frequency distortion, these devices can require additional cooling and can represent a point of failure, but this problem is not unusual. In areas other than RGS, the market volume appears sufficient to justify magnetics optimization.

It was also suggested that significant savings can be achieved if the magnetics were optimally designed with respect to the PCS application. For example, voltage-sourced PCS are connected to a load or grid through an inductor and then a transformer. A transformer can be designed to perform both the voltage transformation and inductive filtering. In volume production, the net cost savings would be substantial.

The potential methods of reducing magnetics cost and footprint are:

- Increase in switching frequency would substantially reduce filtering requirements. Obtaining higher switching frequency will, with present device technologies, necessitate soft-switching technology.

- PCS topologies exist that can eliminate transformers and filters for some applications. Typically these have not been demonstrated in conjunction with ESS or RGS; thus it is difficult to evaluate their savings potential.

- Reduce cost by using use newer technologies for capacitors and inductors. Newer film capacitors are being used in DC links, with as much as a 50% reduction in weight and volume. There does not appear to be any attempt to use newer technologies such as amorphous cores and high-frequency coil design techniques in connection with inductors and transformers. Apparently the design and material costs outweigh benefits in the RGS area.

The magnetics have a significant impact on footprint and cost. However, the key issue appears to be that the cost of modifications may outweigh the benefits in small-volume applications. It is believed that these costs will continue to decline. This area is thus not seen as a major R&D priority.

The objective of this task was to answer the following questions:

1. What type of simplification and standardization is appropriate for PCS used in RGS systems?

2. What are the benefits of such an approach?

The discussions with vendors focussed on PCS design, PCS-related problems in RGS, and the need and approach for standardization. Observations from these discussions are summarized below. An initial analysis of cost savings is also developed.

RGS is a low-volume application, and this makes the design and integration of RGS systems somewhat unique. Most often the PCS vendor acts as the system integrator; that is, the PCS and controls are engineered as one unit. The PCS then becomes the “heart” of the system in the sense that the PCS controller must control the power conversion process as well as control other elements in the RGS. The “true cost” of the PCS is thus masked by costs associated with upgrading the overall control system to include RGS control. The study (PCS study done previously) cites a cost range from \$200–\$1200/kW. Another drawback of existing systems is that although modern PCSs are quite reliable, downtimes can be significant since a failed PCS cannot be easily replaced. This is because the PCS is not an “off-the-shelf” component and usually must be repaired or replaced by the original vendor.

One conclusion, and thus a fundamental assumption in further work, is that in order to specify a minimum functionality PCS it is necessary to separate the RGS control functions and interface hardware from the control functions and hardware required for the power conversion function. This assumption drives the remainder of the discussion.

The benefits of unitizing power electronic subsystems are well recognized in industry, particularly through research originating from the Power Electronic Building Blocks (PEBB) Project.* Although terminology is not completely standardized, industry is moving towards the types of subsystems described below.

- “Power modules,” also called “power assemblies,” are commercially available packages that are comprised of power devices, device drivers, and current/voltage/temperature sensing, cooling, and protection. Devices used and the topological connection depend on function (e.g., DC to three-phase AC conversion) and voltage current ratings. Power modules can include additional components such as DC-side capacitors. With highly optimized design and packaging, and leveraged by markets in the motor control area, the industry target cost for these units is \$25/kW.

- A “power cell” (a term suggested by one of the vendors), a “power processor” or “macro-processor” (a term coined by Silicon Power Co.), would be comprised of the power module and a controller that achieves a specific conversion function. Such a controller would presumably use microprocessor and digital signal processing technology. In the context of RGS, a power cell would be a DC-AC power converter or inverter capable of supplying a specific AC current based on a reference command. Additionally, such power cells could be designed to inherently allow series/parallel connections for higher ratings. The inclusion of a controller mandates that software development tools be made available to program the controller from basic building-block software. Vendors tend to standardize such design.

- A “basic inverter,” on the other hand, would consist of the power cell, associated filters, disconnect means, and a controller that would interface with the overall RGS controller. Thus the RGS controller might specify a setting for AC power; the inverter control would develop the target current command for its current regulator.

It appears that, analogous to the trend in power modules, power cells can also be highly optimized and characterized in a way that any system integrator can utilize them as a subsystem in a PCS. It is also clear that vendors are already moving in this direction and away from one-of-a-kind designs.

Although the cost of some of the components of the PCS are difficult to assess without detailed design, an estimate of cost of a power cell was developed. The previous study provided cost data for actual and proposed RGS applications. The data are broken down by power stage, controller, and balance of system cost. The power stage cost in the minimum functionality PCS was taken to be the target cost of power modules described above, with a contingency cost for assembly and integration. The cost of the controller is extremely variable and probably dominated by custom control development. It is believed that the controller for a minimum functionality PCS is a mature technology and a reasonable cost was assumed. The balance of system cost was estimated using standard installed cost for electrical equipment. The total cost was then compared with median cost of a small village RGS.

* http://pebb.onr.navy.mil/

It is estimated that PCS cost reduction of 50% may be possible. Rather than the specific percentage cited, it should be emphasized that substantial benefits may accrue by reorganizing designs of RGS and leveraging advances in technology in the power electronics industry. This can be done by developing standardized specifications for a PCS at the power cell or basic inverter level. The reduction comes primarily from the use of advanced technology such as power modules, with costs dictated by a much larger market segment. It should be noted that these benefits are offset to some extent by the need for a RGS controller and possibly additional PCSs for the PV system or battery.

In summary, anticipated benefits of moving towards a standardized power cell or basic inverter approach include:

- Potential reduction in PCS cost,
- Interchangeability of PCS from different vendors in RGS designs,
- Ability to easily replace a failed PCS in an RGS system.

RGS systems continue to be one-of-a-kind designs. The development of an industry-supported specification of PCS as a RGS subsystem, rather than the RGS "controller," is recommended. It is believed that this would move the RGS industry in a direction to utilize the same technology as is used in the larger market such as motor-drive, UPS, and other industrial markets. The concept is not novel. It is noted that vendors are moving in this direction in PCS design. Some vendors already offer basic inverter modules and separate controllers. The ESS Program can help accelerate this development.

EESAT Conference

The ESS Program, under the sponsorship of the DOE and in cooperation with the ESA, took over the responsibility for organizing the Electrical Energy Storage Systems Applications and Technology (EESAT) Conference to be held September 18 to 20, 2000, in the Royal Plaza Hotel, Lake Buena Vista, Florida, at the Disney World resort. The international conference addresses all aspects of ESS technologies including conventional and advanced batteries, ultracapacitors, SMES, flywheels, CAES, pumped hydro, power electronics and control systems, and studies and economic analyses of storage systems. Individual components, system applications, and research into advanced systems and components will also be included in the conference agenda.

Status

A three-person steering committee was established in the third quarter to do the initial organizing for work the conference. The steering committee consisted of the DOE/ESS program manager, the ESA board chair, and the SNL/ESS program manager. The full international conference organizing committee will be chosen early in 2000. To aid the committee in the administrative duties of the conference, a competitive contract was placed with Complete Meeting Concepts (CMC), Inc. in Orlando, Florida. Duties of CMC will include developing a pre-conference schedule and financial plan; preparing and mailing all conference announcements, registration, paper collection and publication; and acting as the prime contact with the conference hotel for the meeting logistics. The steering committee will be responsible for technical aspects of the conference (organizing committee selection, paper review and approval, session arrangements, and overall conference direction).

The contract for the hotel was successfully transferred from the ESA to SNL in February 1999.

A call for papers was issued in September 1999, with abstracts due in January 2000. Technical and economic papers are encouraged. The component areas of interest include the ESS, power electronics, control and data acquisition. The application areas of interest include generation, transmission, distributed resources, distribution power quality (DPQ), energy management, and customer applications. The research areas of interest include advanced systems and components, identification of the potential users and needs for energy storage and the future of the deregulated utility industry. The conference schedule is shown in Table 4-15.

Table 4-15. EESAT 2000 Conference Schedule

Call for papers	September 1999
Abstracts due	January 2000
Final papers	June 2000
Final Agenda	August 2000
EESAT 2000 Conference	September 18-20, 2000

5. References

Alaskan Division of Energy. Statistical Report of the Power Cost Equalization Program, Ninth Edition, 1998.

Anderson, Dr. Max D., and John T. Alt. *Assessment of Costs and Benefits of Battery Energy Storage for Electric Utility Applications*, Document AL-9306, revised March 6, 1995.

Anderson, Dr. Max D., and Xiangling Gao. *A Study to Quantify the Benefits of Adding Storage to a Utility System*, Document AO-4841, revised June 28, 1996.

Anderson, Dr. Max D., and John D. Stickley. *Electric Utility Savings from BESS Applications*, Document AU-7834, revised August 31, 1998.

Atcitty, S., S. J. Ranade, and A. Gray-Fenner. *Summary of State-of-the-Art Power Conversion Systems for Energy Storage Application*, SAND98-2019, Sandia National Laboratories, Albuquerque, New Mexico, September 1998.

Butler, P. C. *Energy Storage for Utility Applications: Phase I – Opportunities Analysis*, SAND94-2605, October 1994.

Power Electronics Building Blocks (PEBB) Program. http://pebb.onr.navy.mil/. U.S. Navy, Office of Naval Research. Updated April 9, 1998.

NERC Policy 10, Draft 3 provides details of changes that are under way for Frequency Responsive Reserve. The document is available at http:/www.nerc.com/~oc/standards/.

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Appendix A:

Data From Vernon BESS Operations

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Table A-1. October 1998 Discharge Data from Vernon BESS Operations (Tables for November and December 1998 are not included because preventive maintenance required the BESS to be offline)

October 1998: 3,050-kW Trigger Level							
Date	Day of the Week		No. of Discharge Operations During Required Demand Period	Average kW During Required Demand Period	Largest Peak During Peak-Shaving Period	Difference Between Largest & Average kW Values (at left)	Lowest SOC During Peak-Shaving Period
10/1/98	Th		895	3057	3446	389	72%
10/2/98	F		870	3053	3449	396	69%
10/3/98	Sa		615	2981	3196	215	93%
10/4/98	Su		895	3030	3169	139	92%
10/5/98	M		785	3052	3455	403	64%
10/6/98	Tu		826	3053	3602	549	69%
10/7/98	W		753	3051	3847	796	78%
10/8/98	Th		99	2970	3160	190	91%
10/9/98	F		597	3029	3491	462	89%
10/10/98	Sa	*No PS*	800	2983	3598	615	-
10/11/98	Su	*No PS*	28	2931	3244	313	-
10/12/98	M		617	3036	3450	414	72%
10/13/98	Tu		676	3050	3496	446	71%
10/14/98	W		772	3051	3696	645	76%
10/15/98	Th	*Note A*	1143	3076	3610	534	-
10/16/98	F	*No PS*	1830	3373	3972	599	-
10/17/98	Sa	*No PS*	-	3002	3572	570	-
10/18/98	Su	*No PS*	-	2754	3105	351	-
10/19/98	M	*No PS*	2017	3224	3810	586	-
10/20/98	Tu	*No PS*	2140	3313	3975	662	-
10/21/98	W	*No PS*	2100	3243	3923	680	-
10/22/98	Th	*No PS*	1284	2011	3703	1692	-
10/23/98	F	*No PS*	1201	3109	3775	666	-
10/24/98	Sa	*No PS*	472	2982	3201	219	-
10/25/98	Su	*No PS*	-	2755	3106	351	-
10/26/98	M	*No PS*	2027	3226	3778	552	-
10/27/98	Tu	*No PS*	2147	3343	4319	976	-
10/28/98	W	*No PS*	2114	3228	3768	540	-
10/29/98	Th	*No PS*	2135	3282	3838	556	-
10/30/98	F	*No PS*	2151	3379	4032	653	-
10/31/98	Sa	*No PS*	(Data logger interrupted)				-
(Note: Data acquired from BESS has 10-s sample rates on discharge and 3-min. on recharge, PS = peak shaving)							
(Note A: PCP #2 (inverter) tripped ~3:30 PM for unknown reasons; peak shaving nullified for the month)							
Largest of the month:					4319		
Average for entire month:			1185	3054	3593		78.0%
Average for weekdays only:			1326	3100	3709		75.1%

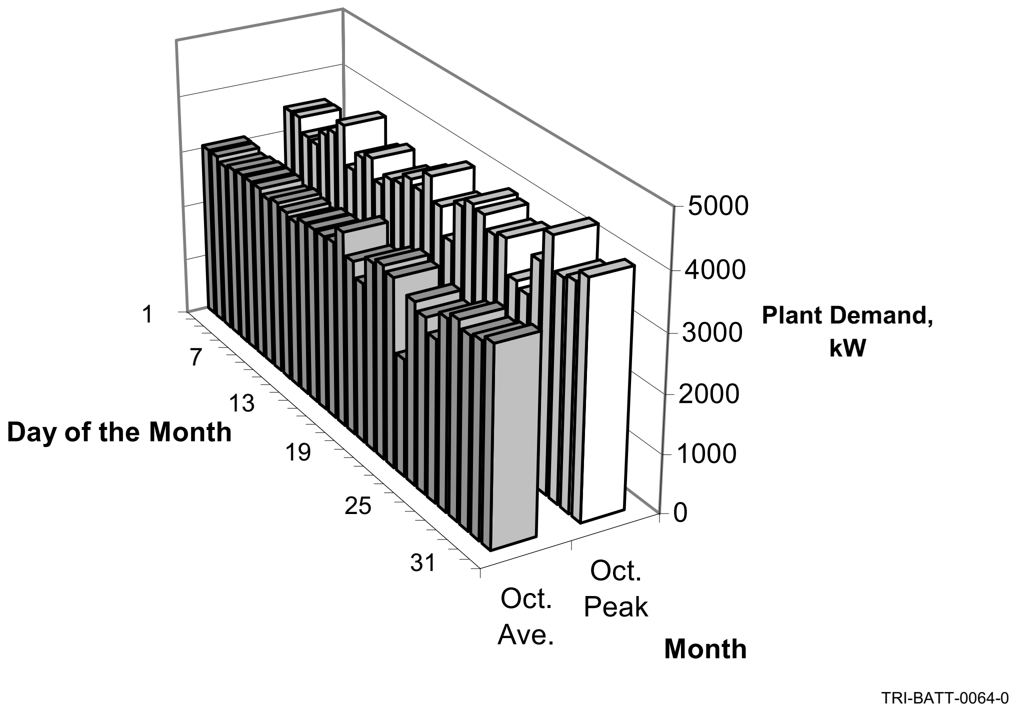

Figure A-1. Average and Peak Plant Demand at Vernon for the Month of October 1998.

Table A-2. January 1999 Data from Vernon BESS Operations

January 1999: 3050-kW Peak-Shaving Trigger Level

Date	Day of the Week		No. of Discharge Operations During Required Demand Period	Average kW During Required Demand Period	Largest Peak During Peak-Shaving Period	Difference Between Largest & Average kW values (at left)	Lowest SOC During Peak-Shaving Period
1/1/99	F		0	2606	2681	75	92 %
1/2/99	Sa	*No PS*	-	2577	2744	167	-
1/3/99	Su	*No PS*	-	2528	2644	116	-
1/4/99	M		26	2739	3283	544	92 %
1/5/99	Tu		0	2502	2861	359	92 %
1/6/99	W		0	2439	2577	138	92 %
1/7/99	Th		29	2699	3310	611	92 %
1/8/99	F		64	2797	3317	520	92 %
1/9/99	Sa	*No PS*	-	2922	3450	528	-
1/10/99	Su	*No PS*	-	2825	3286	461	-
1/11/99	M		75	2767	3341	574	92 %
1/12/99	Tu		196	2907	3383	476	86 %
1/13/99	W		116	2860	3375	515	92 %
1/14/99	Th		193	2914	3382	468	92 %
1/15/99	F		232	2880	3356	476	91 %
1/16/99	Sa	*No PS*	-	2608	2736	128	-
1/17/99	Su	*No PS*	-	2561	2710	149	-
1/18/99	M		270	2948	3342	394	92 %
1/19/99	Tu		220	2908	3284	376	92 %
1/20/99	W		182	2889	3401	512	91 %
1/21/99	Th		33	2766	3273	507	92 %
1/22/99	F		132	2843	3302	459	92 %
1/23/99	Sa	*No PS*	-	2672	2823	151	-
1/24/99	Su	*No PS*	-	2640	2784	144	-
1/25/99	M		586	3039	3404	365	83 %
1/26/99	Tu		273	2938	3394	456	93 %
1/27/99	W		195	2891	3335	444	92 %
1/28/99	Th		112	2839	3376	537	92 %
1/29/99	F		206	2882	3436	554	91 %
1/30/99	Sa	*No PS*	-	2667	2801	134	-
1/31/99	Su	*No PS*	-	2657	2748	91	-

(Note: Data acquired from BESS has 10-sec sample rates on discharge and 3-min on recharge.)
PS = peak shaving

Largest of the month:			3450	
Average for entire month:	150	2765	3134	91.2 %
Average for weekdays only:	151	2755	3110	91.2 %

Table A-3. February 1999 Data from Vernon BESS Operations

February 1999: 3000-kW Peak-Shaving Trigger Level

Date	Day of the Week		No. of Discharge Operations During Required Demand Period	Average kW During Required Demand Period	Largest Peak During Peak-Shaving Period	Difference Between Largest & Average kW values (at left)	Lowest SOC During Peak-Shaving Period
2/1/99	M		142	2842	3346	504	89 %
2/2/99	Tu		184	2849	3324	475	91 %
2/3/99	W		100	2803	3312	509	92 %
2/4/99	Th		15	2708	3220	512	92 %
2/5/99	F		9	2591	3168	577	92 %
2/6/99	Sa		0	2568	2708	140	92 %
2/7/99	Su	*No PS*	-	2613	2689	76	-
2/8/99	M		16	2631	3113	482	92 %
2/9/99	Tu		40	2739	3273	534	92 %
2/10/99	W		62	2733	3281	548	92 %
2/11/99	Th		690	2998	3357	359	83 %
2/12/99	F		761	2992	3398	406	85 %
2/13/99	Sa	*No PS*	-	2832	2993	161	-
2/14/99	Su	*No PS*	-	2838	3015	177	-
2/15/99	M		451	2959	3306	347	89 %
2/16/99	Tu		708	2978	3450	472	87 %
2/17/99	W		602	2996	3356	360	80 %
2/18/99	Th		543	2985	3389	404	86 %
2/19/99	F		577	2984	3352	368	84 %
2/20/99	Sa	*No PS*	-	2788	2916	128	-
2/21/99	Su	*No PS*	-	2725	3012	287	-
2/22/99	M		104	2738	3243	505	92 %
2/23/99	Tu		241	2825	3284	459	92 %
2/24/99	W		336	2881	3372	491	89 %
2/25/99	Th		228	2825	3307	482	91 %
2/26/99	F		661	3001	3386	385	64 %
2/27/99	Sa	*No PS*	-	2886	3107	221	-
2/28/99	Su	*No PS*	-	3044	3183	139	-

(Note: Data acquired from BESS has 10-sec sample rates on discharge and 3-min on recharge.)
PS = peak shaving

	No. of Discharge Operations	Average kW	Largest Peak	Lowest SOC
Largest of the month:			3450	
Average for entire month:	308	2834	3209	87.9 %
Average for weekdays only:	324	2853	3312	87.7 %

Table A-4. March 1999 Data from Vernon BESS Operations

March 1999: 3000-kW Peak-Shaving Trigger Level

Date	Day of the Week		No. of Discharge Operations During Required Demand Period	Average kW During Required Demand Period	Largest Peak During Peak-Shaving Period	Difference Between Largest & Average kW values (at left)	Lowest SOC During Peak-Shaving Period
3/1/99	M		672	2996	3385	389	76 %
3/2/99	Tu		788	3001	3501	500	73 %
3/3/99	W		502	2988	3359	371	83 %
3/4/99	Th		617	2999	3395	396	75 %
3/5/99	F		529	3003	3460	457	80 %
3/6/99	Sa	*No PS*	-	2956	3102	146	-
3/7/99	Su	*No PS*	-	3045	3259	214	-
3/8/99	M		690	3002	3473	471	69 %
3/9/99	Tu		1101	2979	3210	231	90 %
3/10/99	W		1	2920	3076	156	93 %
3/11/99	Th		351	2969	3417	448	91 %
3/12/99	F		584	2982	3356	374	87 %
3/13/99	Sa	*No PS*	-	3005	3216	211	-
3/14/99	Su	*No PS*	-	2920	3073	153	-
3/15/99	M		22	2898	3095	197	93 %
3/16/99	Tu		0	2423	2602	179	92 %
3/17/99	W		0	2368	2492	124	92 %
3/18/99	Th		0	2450	2956	506	92 %
3/19/99	F		0	2498	3166	668	92 %
3/20/99	Sa	*No PS*	-	2615	3342	727	-
3/21/99	Su	*No PS*	-	2895	3199	304	-
3/22/99	M		81	2938	3121	183	91 %
3/23/99	Tu		360	2944	3137	193	82 %
3/24/99	W		554	2952	3159	207	93 %
3/25/99	Th		717	3000	3405	405	80 %
3/26/99	F		124	2838	3060	222	93 %
3/27/99	Sa		824	2968	3084	116	92 %
3/28/99	Su	*No PS*	-	3100	3253	153	-
3/29/99	M		1007	3006	3401	395	69 %
3/30/99	Tu		722	2989	3247	258	82 %
3/31/99	W		873	3000	3341	341	74 %

(Note: Data acquired from BESS has 10-sec sample rates on discharge and 3-min on recharge.)
PS = peak shaving

Largest of the month:			3501	
Average for entire month:	463	2892	3205	84.8 %
Average for weekdays only:	448	2876	3209	84.4 %

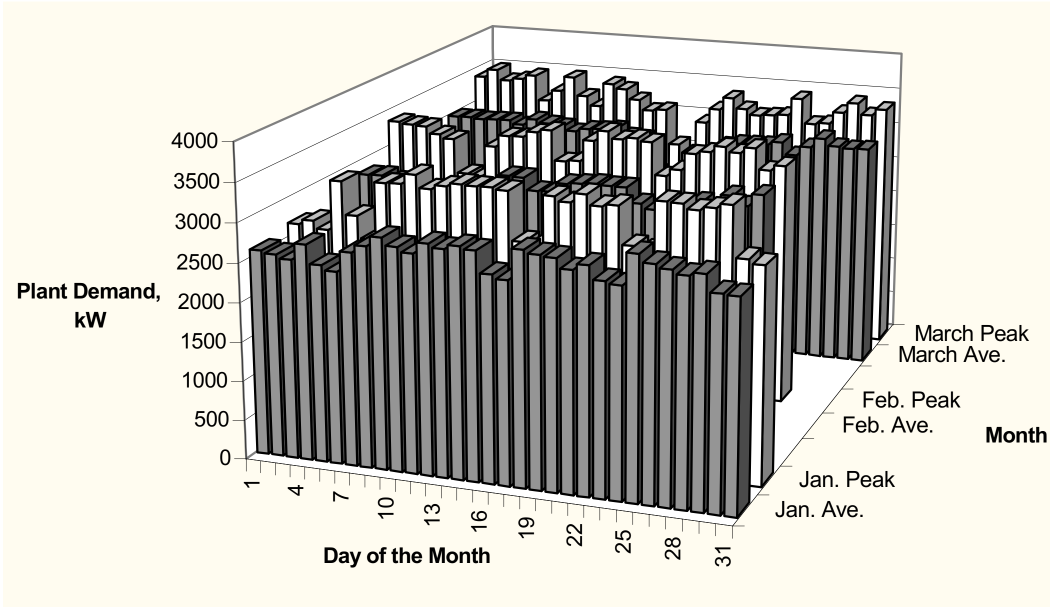

Figure A-2. Average and Peak Plant Demand at Vernon for the Months of January, February, and March 1999.

Table A-5. April 1999 Data from Vernon BESS Operations

April 1999: 2975-kW Peak-Shaving Trigger Level

Date	Day of the Week		No. of Discharge Operations During Required Demand Period	Average kW During Required Demand Period	Largest Peak During Peak-Shaving Period	Difference Between Largest & Average kW values (at left)	Lowest SOC During Peak-Shaving Period
4/1/99	Th		596	2972	3366	394	78 %
4/2/99	F		1054	2972	3112	140	91 %
4/3/99	Sa		1221	2981	3120	139	91 %
4/4/99	Su	*No PS*	-	3085	3242	157	-
4/5/99	M		641	2971	3713	742	71 %
4/6/99	Tu		784	2978	3147	169	84 %
4/7/99	W		779	2964	3322	358	87 %
4/8/99	Th		620	2974	3188	214	82 %
4/9/99	F		36	2932	3080	148	92 %
4/10/99	Sa		0	2848	2945	97	93 %
4/11/99	Su	*No PS*	-	3089	3235	146	-
4/12/99	M		799	2974	3377	403	72 %
4/13/99	Tu		542	2958	3305	347	90 %
4/14/99	W		1114	2978	3373	395	76 %
4/15/99	Th		835	2978	3374	396	70 %
4/16/99	F		529	2962	3073	111	92 %
4/17/99	Sa	*No PS*	-	3023	3228	205	-
4/18/99	Su	*No PS*	-	2996	3176	180	-
4/19/99	M		771	2974	3358	384	62 %
4/20/99	Tu		875	2975	3331	356	60 %
4/21/99	W		543	2926	3396	470	91 %
4/22/99	Th		1465	3059	3521	462	95 %
4/23/99	F		95	2873	3142	269	92 %
4/24/99	Sa	*No PS*	-	3040	3183	143	-
4/25/99	Su	*No PS*	-	3024	3210	186	-
4/26/99	M		689	2976	3337	361	59 %
4/27/99	Tu		905	2981	3515	534	60 %
4/28/99	W		640	2974	3432	458	77 %
4/29/99	Th		898	2972	3322	350	84 %
4/30/99	F		126	2892	3118	226	93 %

(Note: Data acquired from BESS has 10-sec sample rates on discharge and 3-min on recharge.)
PS = peak shaving

	No. of Discharge Operations	Average kW	Largest Peak	Lowest SOC
Largest of the month:			3713	
Average for entire month:	690	2977	3275	80.9 %
Average for weekdays only:	697	2964	3314	79.9 %

Table A-6. May 1999 Data from Vernon BESS Operations

May 1999: 3100-kW Peak-Shaving Trigger Level

Date	Day of the Week		No. of Discharge Operations During Required Demand Period	Average kW During Required Demand Period	Largest Peak During Peak-Shaving Period	Difference Between Largest & Average kW values (at left)	Lowest SOC During Peak-Shaving Period
5/1/99	Sa		497	3014	3313	299	93 %
5/2/99	Su		94	2979	3209	230	92 %
5/3/99	M		769	3089	3571	482	80 %
5/4/99	Tu		526	3045	3527	482	90 %
5/5/99	W		404	3005	3487	482	92 %
5/6/99	Th		367	3011	3462	451	91 %
5/7/99	F		0	2802	2985	183	93 %
5/8/99	Sa		0	2850	3056	206	93 %
5/9/99	Su	*No PS*	-	2833	2942	109	-
5/10/99	M		402	2990	3498	508	89 %
5/11/99	Tu		245	3012	3188	176	93 %
5/12/99	W		98	2923	3445	522	82 %
5/13/99	Th		926	3095	3679	584	83 %
5/14/99	F		119	3070	3452	382	91 %
5/15/99	Sa	*No PS*	-	3031	3860	829	-
5/16/99	Su	*No PS*	-	2930	3196	266	-
5/17/99	M		748	3078	3438	360	87 %
5/18/99	Tu		566	3089	3540	451	74 %
5/19/99	W		590	3082	3536	454	85 %
5/20/99	Th		1063	3092	3463	371	86 %
5/21/99	F		844	3092	3529	437	71 %
5/22/99	Sa	*No PS*	-	3060	3504	444	-
5/23/99	Su	*No PS*	-	3147	3425	278	-
5/24/99	M		911	3099	3547	448	73 %
5/25/99	T		901	3100	3505	405	73 %
5/26/99	W		744	3099	3472	373	89 %
5/27/99	Th		733	3080	3571	491	89 %
5/28/99	F		94	3001	3222	221	92 %
5/29/99	Sa	*No PS*	-	3044	3296	252	-
5/30/99	Su	*No PS*	-	2992	3260	268	-
5/31/99	M	*No PS*	-	3063	3537	474	-

(Note: Data acquired from BESS has 10-sec sample rates on discharge and 3-min on recharge.)
PS = peak shaving

Largest of the month:			3860		
Average for entire month:	506	3026	3410		86.1 %
Average for weekdays only:	553	3044	3460		85.2 %

Table A-7. June 1999 Data from Vernon BESS Operations

June 1999: 3100-kW Peak-Shaving Trigger Level

Date	Day of the Week		No. of Discharge Operations During Required Demand Period	Average kW During Required Demand Period	Largest Peak During Peak-Shaving Period	Difference Between Largest & Average kW values (at left)	Lowest SOC During Peak-Shaving Period
6/1/99	Tu		700	3084	3496	412	82 %
6/2/99	W		471	3069	3543	474	92 %
6/3/99	Th		255	2937	3469	532	91 %
6/4/99	F		610	3030	3500	470	91 %
6/5/99	Sa		0	2746	3029	283	94 %
6/6/99	Su		102	2901	3175	274	92 %
6/7/99	M		408	2992	3485	493	87 %
6/8/99	Tu		394	3024	3472	448	87 %
6/9/99	W		496	3000	3584	584	91 %
6/10/99	Th		575	3057	3571	514	85 %
6/11/99	F		533	2952	3571	619	92 %
6/12/99	Sa	*No PS*	-	2817	3032	215	-
6/13/99	Su	*No PS*	-	2943	3338	395	-
6/14/99	M		382	2991	3453	462	89 %
6/15/99	Tu		228	2960	3450	490	92 %
6/16/99	W		351	2982	3429	447	92 %
6/17/99	Th		207	2945	3406	461	92 %
6/18/99	F		572	3053	3489	436	86 %
6/19/99	Sa	*No PS*	-	2817	3129	312	-
6/20/99	Su	*No PS*	-	2817	3183	366	-
6/21/99	M		432	2979	3442	463	90 %
6/22/99	Tu		472	3021	3491	470	85 %
6/23/99	W		152	2862	3399	537	92 %
6/24/99	Th		575	3044	3468	424	83 %
6/25/99	F		488	3021	3457	436	89 %
6/26/99	Sa	*No PS*	-	2798	3167	369	-
6/27/99	Su	*No PS*	-	2867	3319	452	-
6/28/99	M		87	2834	3307	473	93 %
6/29/99	Tu		463	3004	3461	457	89 %
6/30/99	W		541	3025	3605	580	87 %

(Note: Data acquired from BESS has 10-sec sample rates on discharge and 3-min on recharge.)
PS = peak shaving

Largest of the month:			3605		
Average for entire month:	396	2952	3397		89.3 %
Average for weekdays only:	427	2994	3479		89.0 %

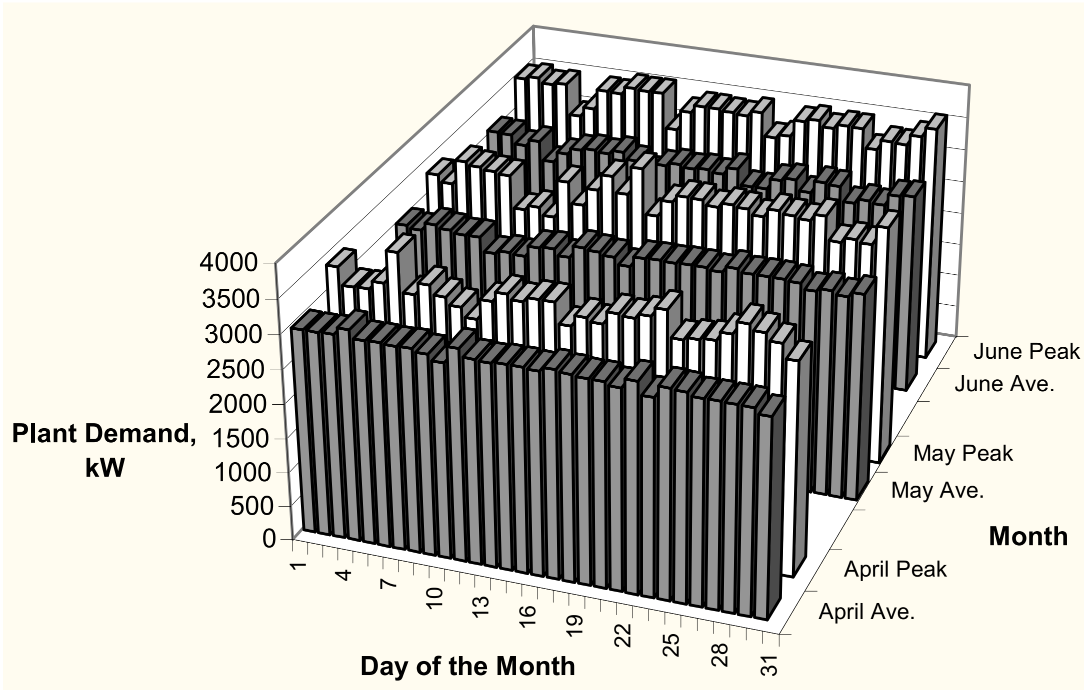

Figure A-3. Average and Peak Plant Demand at Vernon for the Months of April, May, and June 1999.

Appendix B:

Savings Due to BESS Only

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Table B-1. Savings ($k) Due to BESS Only, When Wind Power is Installed

1995	Spinning Reserve			Load Leveling			Load Leveling with Spinning Reserve		
	1	4	8	1	4	8	1	4	8
40	1825	1825	1825	229	508	617	1727	1635	1725
100	3951	3951	3951	437	934	1238	3682	3572	3608
200	6072	6072	6072	677	1480	2211	5930	5970	6116
300	6094	6094	6094	771	1859	2324	6706	7144	7238

1996	Spinning Reserve			Load Leveling			Load Leveling with Spinning Reserve		
	1	4	8	1	4	8	1	4	8
40	1618	1618	1618	229	482	546	1680	1650	1563
100	3986	3986	3986	366	828	930	3586	3280	3266
200	5760	5760	5760	643	1196	1385	5274	5253	5328
300	6008	6008	6008	676	1297	1678	6328	6481	6440

1997	Spinning Reserve			Load Leveling			Load Leveling with Spinning Reserve		
	1	4	8	1	4	8	1	4	8
40	1896	1896	1896	402	765	854	1813	1732	1744
100	3649	3649	3649	727	1427	1695	3386	3407	3421
200	6037	6037	6037	953	1934	1843	5661	5398	5331
300	6059	6059	6059	1120	2170	2141	6723	6622	6521

Table B-2. Savings ($k) Due to BESS Only (no renewables)

1995	Spinning Reserve			Load Leveling			Load Leveling with Spinning Reserve		
	1	4	8	1	4	8	1	4	8
40	1826	1826	1826	560	955	1456	1098	2091	2127
100	3042	3042	3042	584	1718	2767	3297	3564	3779
200	3781	3781	3781	933	2371	3153	4389	4773	4900
300	3637	3637	3637	1019	3028	3963	4926	5739	6381
1995	**Spinning Reserve**			**Load Leveling**			**Load Leveling with Spinning Reserve**		
	1	4	8	1	4	8	1	4	8
40	945	945	945	284	516	690	674	1540	1577
100	3136	3136	3136	458	132	1656	3053	3054	3256
200	4838	4838	4838	793	2095	3213	3965	4404	5010
300	4744	4744	4744	850	2594	3861	4682	5805	6757
1997	**Spinning Reserve**			**Load Leveling**			**Load Leveling with Spinning Reserve**		
	1	4	8	1	4	8	1	4	8
40	1632	1632	1632	229	610	965	1681	1820	1838
100	2764	2764	2764	451	1222	1997	2752	2767	2955
200	4435	4435	4435	851	2161	3112	4936	5285	5578
300	4520	4520	4520	1163	2929	3961	5799	6764	7556

Appendix C:

Presentations and Publications

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Appendix C:

Presentations and Publications

Presentations

A. Akhil, “Battery and Diesel Concepts,” presented at the Rural Alaska Alternative Energy technical conference, Fairbanks, Alaska, August 17, 1999.

S. Atcitty, “Power Conversion System Analysis,” PCS Study—presented at the DOE Executive Review meeting, Washington, DC, September 8 through 9, 1999.

J. D. Boyes, P.C. Butler, “Energy Storage is Underway at Sandia National Laboratories (DOE),” presented at the ESA spring meeting, Raleigh, North Carolina, May 6, 1999.

J. D. Boyes, “Substation Power Quality Project,” presented at the Power Systems World Conference, Santa Clara, California, November 1998.

J. D. Boyes, “Transmission Power Quality Project,” Southeast Electric Exchange Power Quality Subcommittee meeting – New Orleans, Louisiana, April 1999.

J. D. Boyes, “Status of Energy Storage Program,” presented at the ESS Annual Peer Review, Washington DC, September 1999.

J. D. Boyes, “Lessons Learned in the Puerto Rico Battery Energy Storage Project,” presented at the Sixth International Batteries for Utility Energy Storage Conference, Essen, Germany, September 1999.

J. D. Boyes, “Demonstrations of Utility Sized Zinc/Bromine Battery Systems,” presented at the Sixth International Batteries for Utility Energy Storage Conference, Essen, Germany, September 1999.

J. D. Boyes, “A Pilot Renewable/Diesel Hybrid Village System in Mexico,” presented at the Sixth International Batteries for Utility Energy Storage Conference, Essen, Germany, September 1999.

P. C. Butler, “Energy Storage Simulator Applications and Enhancements,” presented at the NRECA Power Supply Task Force meeting, Albuquerque, New Mexico, January 1999.

P. C. Butler, “ILZRO/SNL VRLA Reliability Study,” presented at 111th BCI convention, Nashville, Tennessee, May 4, 1999.

G. P. Corey, “Intermediate State of Charge Testing Program,” presented at the spring ESA meeting, Raleigh, North Carolina, May 7, 1999.

P. DiPietro, “Analysis of Flywheels & SMES in Stationary Applications,” presented at the ESA spring meeting, Raleigh, North Carolina, May 7, 1999.

M. McIntyre, “Database for Alaska Community Electric Power Systems,” presented at the Fourth Annual Science and Technology Outreach symposium, Albuquerque, New Mexico, August 5, 1999.

C. Namovicz, R. Sen, N. Miller, “Advanced Lithium Batteries for Stationary Applications,” presented at the spring ESA meeting, Raleigh, North Carolina, May 7, 1999.

D. Rovang, A. A. Akhil, J. D. Boyes, “Substation Power Quality Project,” presented at the ESA spring meeting, Raleigh, North Carolina, May 7, 1999.

R. Sen, “Renewable Generation and Storage,” presented at the ESA spring meeting, Raleigh, North Carolina, May 7, 1999.

P. A. Taylor, P. T. Moseley, P. C. Butler, “Preliminary Results of an ILZRO-Sponsored Field-Data Collection and Analysis to Determine Relationships Between Service Conditions and Reliability of VRLA Batteries in Stationary Applications,” presented at the Intelec 98 conference, San Francisco, California, October 7, 1998.

W. Torres, “Four Years of Experience with the PREPA BESS,” presented by P.C. Butler at the 111th BCI convention, Nashville, Tennessee, May 4, 1999.

Publications

J. D. Boyes, *Lessons Learned from the Puerto Rico Battery Energy Storage System*, English and Spanish versions available, SAND99-2232, Sandia National Laboratories, Albuquerque, New Mexico, September 1999.

J. D. Boyes, *Lessons Learned in the Puerto Rico Battery Energy Storage Project*, Sixth International Batteries for Utility Energy Storage Conference, Essen, Germany, September 1999.

P. C. Butler, *Energy Storage Systems Program Report* for FY98, SAND98-0883, Sandia National Laboratories, Albuquerque, New Mexico, April 1999.

N. C. Clark, P. Eidler, and P. Lex, *Development of Zinc/Bromine Batteries for Load-Leveling Applications: Phase 2 Final Report*, SAND99-2691, Sandia National Laboratories, Albuquerque, New Mexico, October 1999.

P. Eidler, *Development of Zinc/Bromine Batteries for Load-Leveling Applications: Phase 1 Final Report*, SAND99-1853, Sandia National Laboratories, Albuquerque, New Mexico, July 1999.

C. Miralles, B. Jensen, A. Flack, B. Yelin, J. Cromwell, R. Lopez, and S. Berge, *Solar-Powered Systems for Environmental Remediation,* SAND99-0936, Sandia National Laboratories, Albuquerque, New Mexico, April 1999.

B. L. Norris and G.J. Ball, *Performance and Design Analysis of a 250-kW, Grid-Connected Battery Energy Storage System*, SAND99-1483, Sandia National Laboratories, Albuquerque, New Mexico, June 1999.

P. Taylor, L. Johnson, K. Reichart, P. DiPietro, J. Philip, and P. Butler, *A Summery of the State of the Art of Superconducting Magnetic Energy Storage Systems, Flywheel Energy Storage Systems, and Compressed Air Energy Storage Systems*, SAND99-1854, Sandia National Laboratories, Albuquerque, New Mexico, July 1999.

J. Wohlgemuth, J. Miller, and L. B. Sibley, *Investigation of Synergy Between Electrochemical Capacitors, Flywheels, and Batteries in Hybrid Energy Storage for PV Systems*, SAND99-1477, Sandia National Laboratories, Albuquerque, New Mexico, June 1999.

G. Kern, *System and Battery Charge Control for PV-Powered AC Lighting Systems,* SAND99-0935, April 1999.